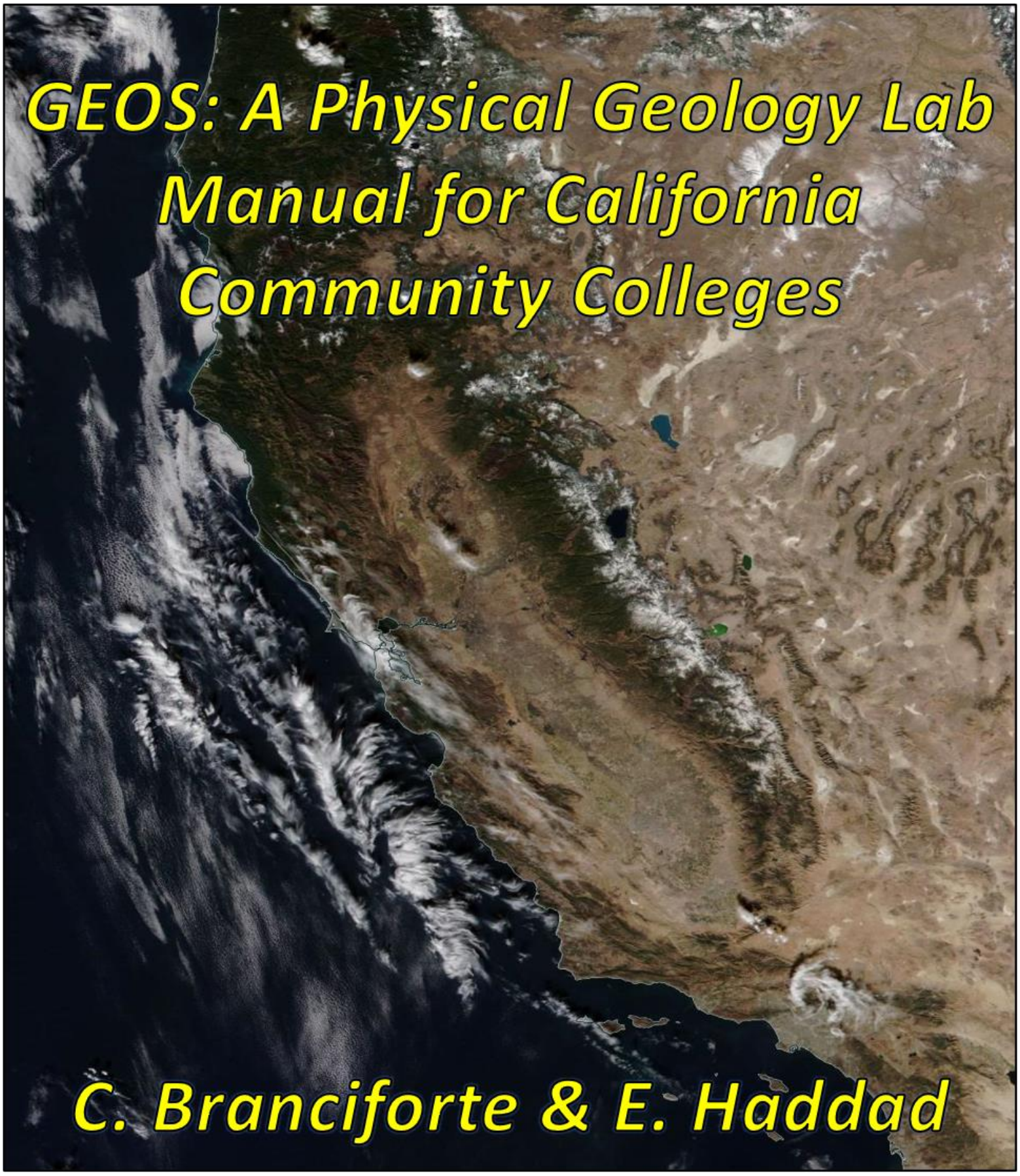
GEOS: A Physical Geology Lab Manual for California Community Colleges
C. Branciforte & E. Haddad

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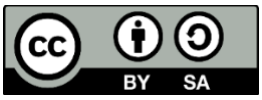

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- Physical Geology 2nd Edition by Steven Earle from Vancouver Island University. CC-BY
- An Introduction to Geology by Chris Johnson, Matthew D. Affolter, Paul Inkenbrandt, Cam Mosher from Salt Lake Community College. CC-BY-NC-SA
- Laboratory Manual for Introductory Geology by Bradley Deline, Randa Harris, and Karen Tefend from the University of West Georgia. CC-BY-SA.

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How Do I Use This Lab Manual?

This manual is provided as an **Open Educational Resource** and can be accessed online. Key-terms have been **bolded** and/or hyperlinked to provide quick access to definitions and information. Where appropriate, images and links to videos and/or websites have been provided to support content and lab activities. The manual was designed to be used by California Community Colleges for Physical Geology Laboratory (C-ID, GEOL 100L or GEOL 101). The following course objectives were used during the construction of this manual.

Course Objectives for C-ID GEOL 100L

1. Practically apply the principles of the scientific method.
2. Demonstrate a conceptual understanding of fundamental concepts, principles, and interactions of Earth's systems applicable to the Geological Sciences.
3. Demonstrate an understanding of the Earth through the identification and evaluation of physical mineral samples.
4. Demonstrate an understanding of the Earth through the identification and evaluation of physical igneous, sedimentary, and metamorphic rock samples.
5. Demonstrate an ability to communicate complex course concepts effectively in writing and diagrams.
6. Demonstrate the ability to read and interpret topographic and geologic maps and answer questions pertaining to geologic processes.

To Faculty:

In February 2020, ASCCC approved our proposal (*GEOS-Geoscience Equity Opportunities for Students: Making the Earth Accessible through an OER Physical Geology Laboratory Manual*) to develop this lab manual. Within weeks, COVID-19 happened and we, like many of you, found ourselves rapidly transitioning our courses to be fully online. As a result, it was important we ensure the activities here could be supported and completed successfully in any modality (in-person, online, hybrid).

Within this manual we have worked to curate the most current content, websites, data, and resources available for introductory geology community college students. The twenty (20) distinct chapters provide flexibility and allow selection based on need. Not every district or school will have access to identical resources. In lieu of making assumptions on availability, we instead prompt students to "ask their instructor", which grants the instructor the final say. Should you need additional geology imagery (samples, landforms, etc.), visit the Flickr page of James St. John (The Ohio State University at Newark). All images are licensed CC-BY and have incredible resolution. Where appropriate, California-specific geology was incorporated into each chapter, with representative material from across the state.

Lastly, if there is something you would like to see added or would like to share material you have already created, please send us an email; we are already contemplating the second edition!

To Students:

This lab manual was designed for you and we hope you enjoy the California-centric material and mix of hands-on and online activities. Whether you live in southern, central, or northern California, you have access to spectacular geology; get out and explore your local region (if safe to do so). Upon completion of this course, we hope you recognize the importance of the Geosciences to our modern life and society and begin to see the incredible potential of geology.

This manual uses the browser version of Google Earth. To familiarize yourself with this program, read through Google's help page and play around within the program itself. Each chapter will contain **bolded** and/or hyperlinked key terms. Some chapters will have a "Can You Dig It" (CYDI) section, which contain topical items typically of interest to students.

Most students remain unaware of geology career options. In this manual, we have included sections in each chapter illustrating career possibilities and how to pursue those opportunities. For detailed career information read through the following.

Earning a Geology Degree

Some entry-level geology careers require a bachelor's degree; however, better jobs with opportunities for advancement typically require a master's degree or PhD. A research geologist or work within a 4-year university will often require a PhD.

In California, many community colleges have an **Associate Degree for Transfer (ADT) in Geology**, which is fully transferable to schools within the California State University, and on a case-by-case basis for schools within the University of California system. Currently, courses required for the ADT include physical geology and lab (C-ID GEOL 101 or GEOL 100 and 100L), historical geology and lab (C-ID GEOL 111 or GEOL 110 and 110L), general chemistry for science majors' sequence (C-ID CHEM 120S), calculus I & II (C-ID MATH 210 and 220 or MATH 211 and 221 or MATH 900S), and all GE electives (CSU GE-Breath or IGETC). For the most up to date information regarding transfer model curriculum visit the C-ID site. We highly encourage you to discuss careers options with an instructor and/or counselor.

While pursuing a degree, many students find important work experience and networking potential during an **internship**. Many of these internships are open to community college students, which means you do not need wait until you transfer to apply. Oftentimes applications require a letter of recommendation; talk with your instructor if interested. Don't

hesitate to apply, these opportunities are incredibly valuable and can provide insight into your future career.

Popular Geology Internship Programs

- American Geosciences Institute
- Geological Society of America – Geoscientists in the Parks (GIP)
- Geological Society of America – GeoCorps America
- Incorporated Research Institutions for Seismology (IRIS)
- Monterey Bay Aquarium Research Institute (MBARI)
- NASA – Jet Propulsion Laboratory (JPL)
- Southern California Earthquake Center (SCEC)
- Smithsonian Museum of Natural History
- United States Department of Interior – Bureau of Land Management (DOI – BLM)
- United States Geological Survey
- Woods Hole Oceanographic Institution

What Does a Geologist Do?

Geologists typically study the structure, composition, and history of the Earth, some even examine other planets and bodies in the Solar System. A geologist is more than identifying rocks and minerals. They examine the natural processes affecting the Earth, explore for resources such as water, oil, and gas, study the fossil remains of plants and animals, and consider the effects of the elements, earthquakes, or volcanoes on landforms.

Most geologists divide their time among **field research**, where they may collect data, samples, or measure strata, laboratory work, where they analyze data, samples, conduct experiments or computer modeling, and the "office" where they write papers, reports or draft maps and diagrams showing the results of their studies. Geology is rapidly evolving and looks very different than it did even a decade ago. Modern geologists are comfortable working with technology, including social media, and commonly work in **interdisciplinary** and/or **multidisciplinary** teams.

Many geologists are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey (CGS) or United States Geological Survey (USGS). Additional career pathways are available in the private sector including mining and natural resource extraction, environmental policy, legislation, and consulting. Many of these careers require a college degree and postgraduate work (typically a PhD). If you are interested in geology, talk to you instructor for advice. We recommend completing as many math and science courses as possible. Also visit National Parks, California State Parks, museums, gem & mineral shows, or join a local rock and mineral club, or other

geology-centered organization (many are open to students for free or at a reduced rate). Typically, natural history museums will have wonderful displays of rocks, minerals, and fossils, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, La Brea Tar Pits and Museum, Santa Barbara Museum of Natural History, and the Kimball Museum of Natural History. Additionally, many colleges and universities also have their own collections/museums. If you are unsure of what your region offers, oftentimes a simple Google search (example, rock and mineral organizations nearby) will help determine what is available. Below are just a few potential career options for those with a geology degree,

- Curator of a Natural History Museum
- Economic Geologist
- Engineering Geologist
- Environmental Geologist
- Environmental Impact Report Writer
- Exploration Geologist
- Field Geologist
- Geochemist
- Geophysicist
- Geochronologist
- Geological Consultant
- Geothermal Energy Specialist
- Groundwater Geologist
- Hydrologist/Hydrogeologist
- Instructor/Lecturer/Professor
- Laboratory Assistant/Technician
- Marine Geologist
- Mineralogist
- Mining Geologist
- Naturalist
- Paleontologist
- Park Ranger
- Petroleum Geologist
- Petrologist
- Planetary Geologist (Astrogeology)
- Planner
- Research
- Assistant/Technician
- Seismologist

- Stratigrapher
- Structural Geologist
- Technical Writer/Editor
- Paleontologist
- Volcanologist
- *and many more!*

Where Are Geologists Employed?

- Colleges, Universities and Museums
- Engineering, Construction & Consulting Firms
- Federal agencies:
    - Army Corps of Engineers
    - Bureau of Land Management
    - Bureau of Reclamation
    - Department of Energy
    - EPA
    - US Forest Service
    - US Geological Survey
    - NASA
    - National Laboratories
    - NOAA
    - National Park Service
- Non-profit research institutions
- State/Local agencies
    - CA Department of Conservation
    - California Geological Survey
    - CalTrans
- Resource Extraction
- Utility companies

Join a National, Regional, or Local Geoscience Organization

- American Association of Petroleum Geologists (AAPG)
    - Pacific Section AAPG
- American Gem Society (AGS)
- American Geosciences Institute (AGI)
- American Geophysical Union (AGU)
- Association for the Sciences of Limnology and Oceanography (ASLO)
- Association for Women Geoscientists (AWG)
- Association of Environmental & Engineering Geologists (AEG)
- The Clay Minerals Society (CMS)
- California Council of Geoscience Organizations (CCGO)
- California Independent Petroleum Association (CIPA)
- California Well Sample Repository (CWSR)
- Environmental and Engineering Geophysical Society (EEGS)
- Geological Society of America (GSA)
- Geologists' Association (GA)
- Gemological Institute of America (GIA)
- Geoscience Information Society (GSIS)
- Inland Geological Society (IGS)
- International Association of Hydrological Sciences (IAHS/AISH)
- International Association for Mathematical Geosciences (IAMG)
- International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI)
- International Commission on Stratigraphy (ICS)
- International Glaciological Society (IGS)
- International Union of Geodesy and Geophysics (IUGG)
- International Union of Geological Sciences (IUGS)
- International Union of Soil Sciences (IUSS)
- Mineralogical Society of America (MSA)
- Mineralogical Society of Southern California (MSSC)
- National Association of Black Geologists and Geophysicists (NABGG)
- National Association of Geoscience Teachers (NAGT)
- National Cooperative Soil Survey (NCSS)
- National Society of Consulting Soil Scientists (NSCSS)
- National Speleological Society (NSS)
- Northern California Geological Society (NCGS)
- Paleontological Research Institution (PRI)
- Paleontological Society (PS)
- Rocky Mountain Association of Geologists (RMAG)

- Seismological Society of America (SSA)
- American Institute of Mining, Metallurgical, and Petroleum Engineers (SME)
- San Diego Association of Geologists (SDAG)
- San Joaquin Geological Society (SJGS)
- Society for Sedimentary Geology (SEPM)
- Society of Economic Geologists (SEG)
- Society of Exploration Geophysicists (SEG)
- Society of Mineral Museum Professionals (SMMP)
- Society of Petroleum Engineers (SPE)
- Society of Petrophysicists and Well Log Analysts (SPWLA)
- Society of Vertebrate Paleontology (SVP)
- Soil Science Society of America (SSSA)
- Woods Hole Oceanographic Institution

Who Are We?

Professor Chloe Branciforte

Professor Branciforte is an Associate Professor of Geology at Ventura College in Ventura, California. She has a Master of Science in paleontology from South Dakota School of Mines and Technology, and a Bachelor of Science in Geology from SUNY Buffalo in New York. Professor Branciforte specializes in vertebrate paleontology, specifically small mammals (i.e., rodents), and has been teaching geology for more than a decade. When she was 9, Professor Branciforte had the opportunity to participate in a fossil hunting day with a local museum and her Girl Scout troop. She found her first fossil that day and knew she wanted to be a paleontologist.

Dr. Emily Haddad

Dr. Haddad is an Assistant Professor of Geology at East Los Angeles College in Monterey Park, California. She has a PhD in organic geochemistry and paleoecology from the University of California at Riverside, with a focus on extinction, black shales, and ancient microbial ecology, and an A.B. in Government and Earth and Planetary Sciences from Harvard University. Dr. Haddad decided she was going to be a paleontologist when she was 5 years old but took a detour though political science as an undergraduate, before returning to her first passion in graduate school.

Chapter 1: An Introduction to Science and the Geosciences

Learning Outcomes

After completing this chapter, you should be able to:

- ✓ Describe the scientific method.
- ✓ Construct and document geoscientific observations.
- ✓ Identify the five spheres (reservoirs) of the Earth System.
- ✓ Identify and analyze major cycles that connect the spheres of the Earth System.
- ✓ Calculate, and directly measure items as they relate to geology.

Thumbnail for Chapter 1:

Thumbnail: "Western hemisphere" (Public Domain; Reto Stöckli for NASA

What Is Science?

Science is not just a subject: it's a way of thinking. Science is the process used to objectively investigate the universe and everything in it. Geoscience, including geology, offers an important perspective for understanding our world! As geoscientists, we study the Earth of the past, present, and, sometimes, the future.

In previous classes, you may have encountered the **scientific method**; however, it is worthwhile to review as it is foundational to any science course. The first stage of the scientific method is observation. An **observation** requires using the five senses to engage with the world around you. Observations may be simple, like identifying the outward color of a mineral. Sometimes, however, observations will require you to learn basic background information through an experiment or test. For example, testing the streak of a mineral will require you to rub the mineral across a porcelain plate. This can produce a colored powder that can then be recorded. It is important to always document observations. Many geoscientists record their observations in a **field notebook** or on a computer. Documentation ensures records can be accessed in the future, and methods can be duplicated by others. Oftentimes, your observations will lead to questions. In fact, you may find yourself with many questions; this is okay! You may even find yourself repeating the observation portion of the scientific method many times in order to feel confident to move forward in the process. This is also okay, because your continued investigation keeps the process of science alive.

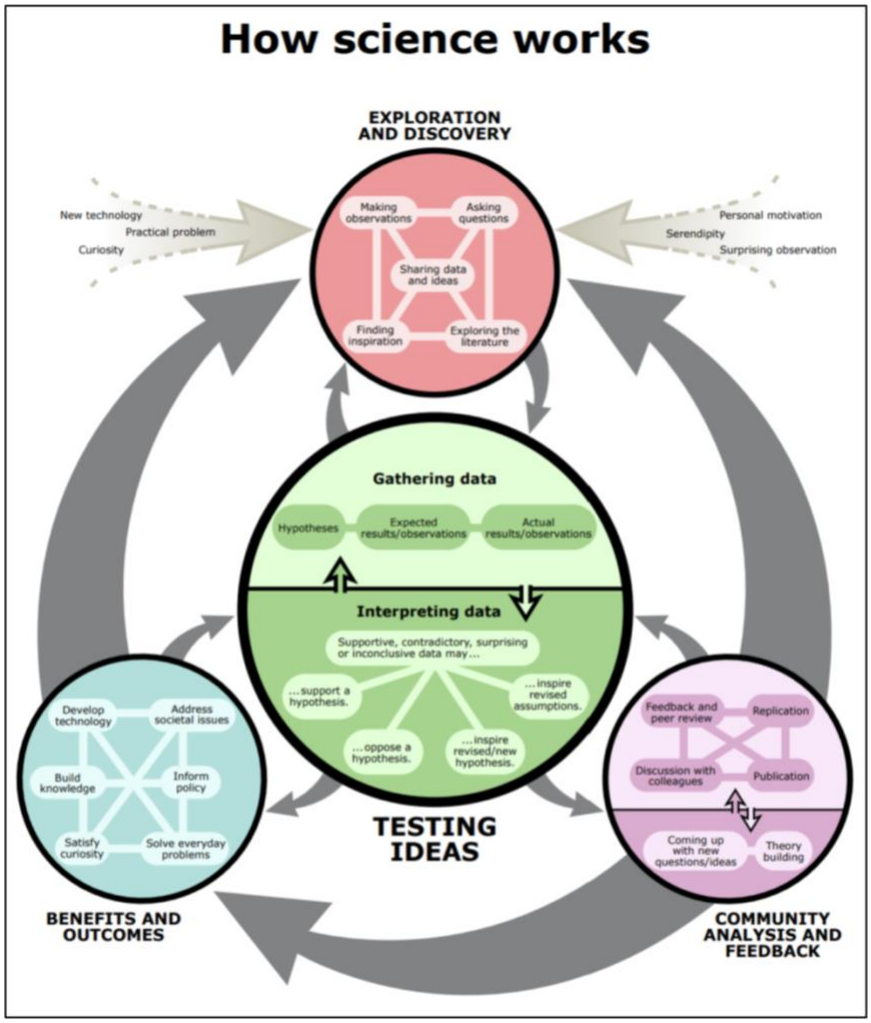


Figure 1.1: In contrast to the linear steps of the simplified scientific method, the process of science is non-linear.

The questions generated during the observation stage can be constructed into a hypothesis. A **hypothesis** is a testable prediction of how something works. A

hypothesis should be framed in such a way that it is easy to test. Science works to rigorously disprove a hypothesis. Only hypotheses that withstand the rigor of testing become accepted. Regardless of whether a hypothesis is verified or rejected, new information will be gained. When a hypothesis is rejected, this does not equate to failure of the experiment. Instead, it is a prompt to revisit the original observations, make new ones, ask new questions, and form new hypotheses to test.

The final stage of the scientific method is **communication**. This stage is often skipped in traditional discussions of the scientific method, but it is very important, and, with the advent of the internet and social media, has become considerably easier to accomplish. Communication within the scientific community allows for experiments to be replicated in novel ways, expanding the original hypothesis and addressing questions from many perspectives. This is why a diverse scientific community is so important! Our *"Scientist Spotlights"* highlight diverse Geoscientists from their respective fields; we hope you enjoy each short biography.

In addition to communication within the scientific community, communication with the general public is also important. This can be done through a press conference, news report, written article, or via social media, blogging or vlogging. Many scientists have taken to social media, which has encouraged a rapid, global exchange of information. Check out **#ScienceTwitter**, **#SciComm**, and **#ScienceComm** for a wealth of science information. As with everything on the internet, be cautious and critically evaluate your sources. Be open to new information and willing to adapt and change your mind when confronted with data, evidence, and facts. If you have an interest in science and journalism, many institutions now offer science communication or **science journalism** degrees at all levels.

During an individual scientist's career, they will often only participate in a small portion of the scientific method. Hundreds of related observations and tested hypotheses accumulate for scientists to formulate a theory. A **scientific theory** is an explanation for a natural phenomenon that is *supported by a wealth of scientific data*. A theory is not yet a **scientific law** if there is still some debate on the exact workings of the theory or the reasons why a phenomenon occurs.

Attributions

- Figure 1.1: Understanding Science: How Science Works. ©University of California Museum of Paleontology. Used with permission (13 November 2020). [All rights reserved].

What Are the Geosciences?

Earth is a complex and dynamic place, with many moving components and processes. **Geoscience (Earth Science)** examines the Earth: a considerably massive subject. Take a minute to think about everything you encounter every day that is connected with Earth. Is your mind blown yet? Welcome to the career of a geoscientist! A **geoscientist** is someone who studies the Earth System. Geoscientists have varied and diverse careers. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways include environmental policy, legislation and consulting, or science communication via the private sector or state and federal agencies. Many of these career options require a college degree and postgraduate work. If you are interested in the geosciences, talk with your geology instructor for advice.

Quick Facts: Geoscientists	
2019 Median Pay	$92,040 per year $44.25 per hour
Typical Entry-Level Education	Bachelor's degree
Work Experience in a Related Occupation	None
On-the-job Training	None
Number of Jobs, 2018	31,000
Job Outlook, 2018-28	6% (As fast as average)
Employment Change, 2018-28	1,800

Figure 1.2: Quick facts regarding a geoscience career.

The broad range of subjects within geoscience are frequently **multidisciplinary**, involving cross-over with many other fields including STEM (Science, Technology, Engineering and Mathematics), Social Sciences, and the Arts. A geoscientist typically solves problems using an **interdisciplinary** approach. This requires them to work with and learn from many fields to address diverse questions. For example, a paleoclimatologist, a scientist who studies climates of the past, searches for information about past climate through ice or sediment cores, fossils, and rocks. The information they collect can be used to understand climate through past geologic time but also current and future climate change. Their research can be utilized for hazard mitigation, planning, and preparation at the city, county, state, and federal levels.

Because of the interdisciplinary nature of the geosciences, we recommend completing as many math and science courses as possible. Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum,

Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Within the geosciences, there is the discipline **geology**, the scientific study of the Earth. In general, geology has two major branches of study: 1) **Physical Geology**, which focuses primarily on what the Earth is composed of and how its processes work beneath and at the surface, and 2) **Historical Geology**, which examines the evolution of Earth through geologic time. There are aspects of geology that are directly testable and others that cannot be directly tested. Geologists must use their imagination to discover aspects about the Earth and its history that we cannot directly observe.

Within this physical geology laboratory manual, we will focus on materials that make up the Earth, like minerals and rocks, and Earth processes, including plate tectonics, weathering and erosion, and many others. The topics covered in this manual are varied and well-suited for an introductory level community college course. We hope that you enjoy the topics and become more curious about the world around you!

Figure 1.3: Western hemisphere of Earth from space.

Attributions

- Figure 1.2: “Quick Facts: Geoscientists” (Public Domain; US Bureau of Labor Statistics)
- Figure 1.3: “Western hemisphere” (Public Domain; Reto Stöckli for NASA)

Activity 1A: Thinking Like a Geoscientist

1. In your own words, describe the Earth System. What is included within the system of the Earth?

2. In the table below are the five spheres (reservoirs) of the Earth System. What items of the Earth System have you encountered this week? Place each item in its appropriate reservoir and indicate whether it is a solid (S), liquid (L), or gas (G).

Atmosphere	Hydrosphere	Cryosphere	Biosphere	Geosphere

3. Was identifying these items challenging? Why or why not?

4. Based on your observations from Question 2, determine what you believe is the common or typical state of matter (solid, liquid, or gas) for materials in each reservoir. Record your hypotheses in the table below.

Atmosphere	Hydrosphere	Cryosphere	Biosphere	Geosphere

Activity 1B: Connections Between the Reservoirs

1. Consider the five spheres of the Earth System. How do you think energy and matter are exchanged between and among the five spheres? Provide an example to explain your thoughts.

2. How does the Earth System change over time? Provide an example to explain your thoughts.

Activity 1C: Earth Cycles

Energy and matter are exchanged by **cycles** between the spheres of the Earth System. These cycles connect all of Earth's reservoirs together.

1. Select a cycle from those listed below. Search the internet for information regarding your cycle.
    a. Which spheres does the cycle connect?

    b. How do you think this cycle is important to geology?

The Hydrologic (Water) Cycle

The **hydrologic cycle** involves the continuous circulation of water in the Earth-Atmosphere system. At its core, the water cycle is the motion of the water from the ground to the atmosphere and back again. Of the many processes involved in the hydrologic cycle, the most important are, **evaporation**, **transpiration**, **condensation**, **precipitation**, and **runoff**.

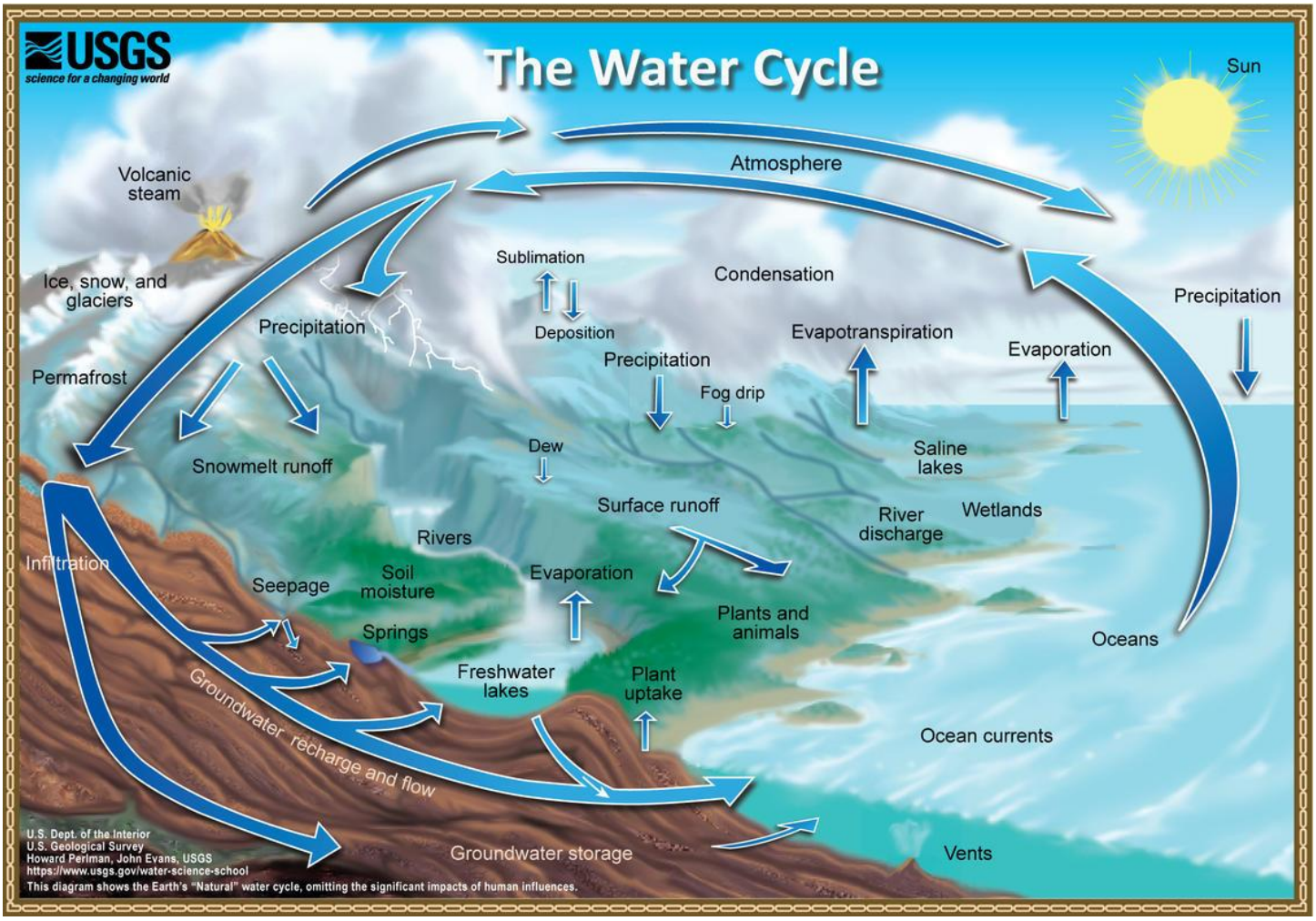


Figure 1.4: Earth's water is always in movement, and the natural water cycle (hydrologic cycle), describes the continuous movement of water on, above, and below the surface of the Earth. Water is always changing states between liquid, vapor, and ice, with these processes happening in the blink of an eye or over millions of years.

Wilson (Plate Tectonic) Cycle

Movement of the tectonic plates through time to rift continents. This cycle initiates with a continental rift which breaks up a continent, and leads to the formation of an ocean basin between two lithospheric plates.

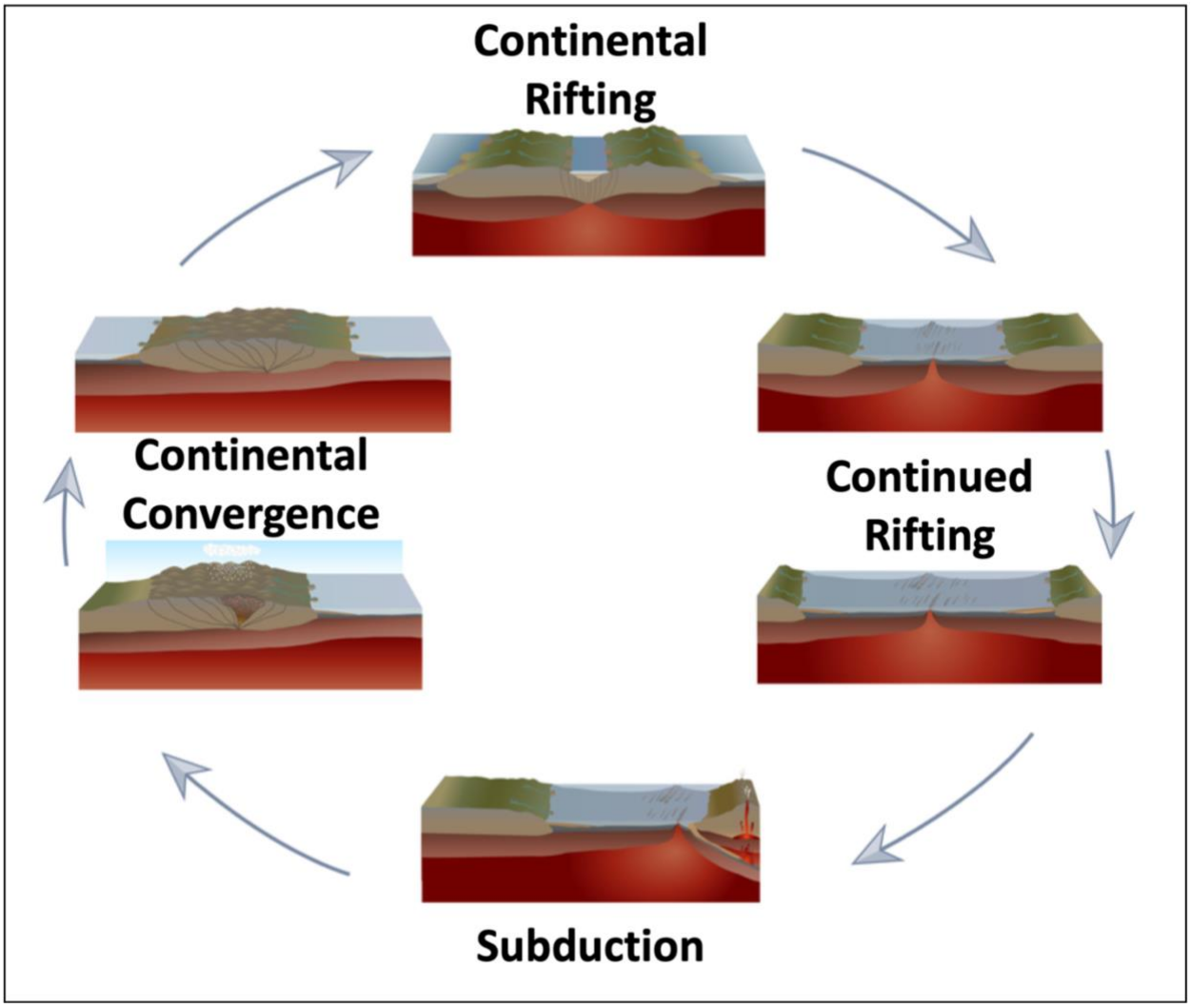


Figure 1.5: An overview of the Wilson Cycle. Movement of the tectonic plates through time to rift continents. This cycle initiates with a continental rift which breaks up a continent and leads to the formation of an ocean basin between two lithospheric plates.

Milankovitch Cycles

Milankovitch cycles are related to Earth's place in space, sometimes referred to as the exosphere. The shape of Earth's orbit (**eccentricity**), angle Earth's axis is tilted with respect to Earth's orbital plane (**obliquity**), and the direction Earth's axis of rotation is pointed (**precession**).

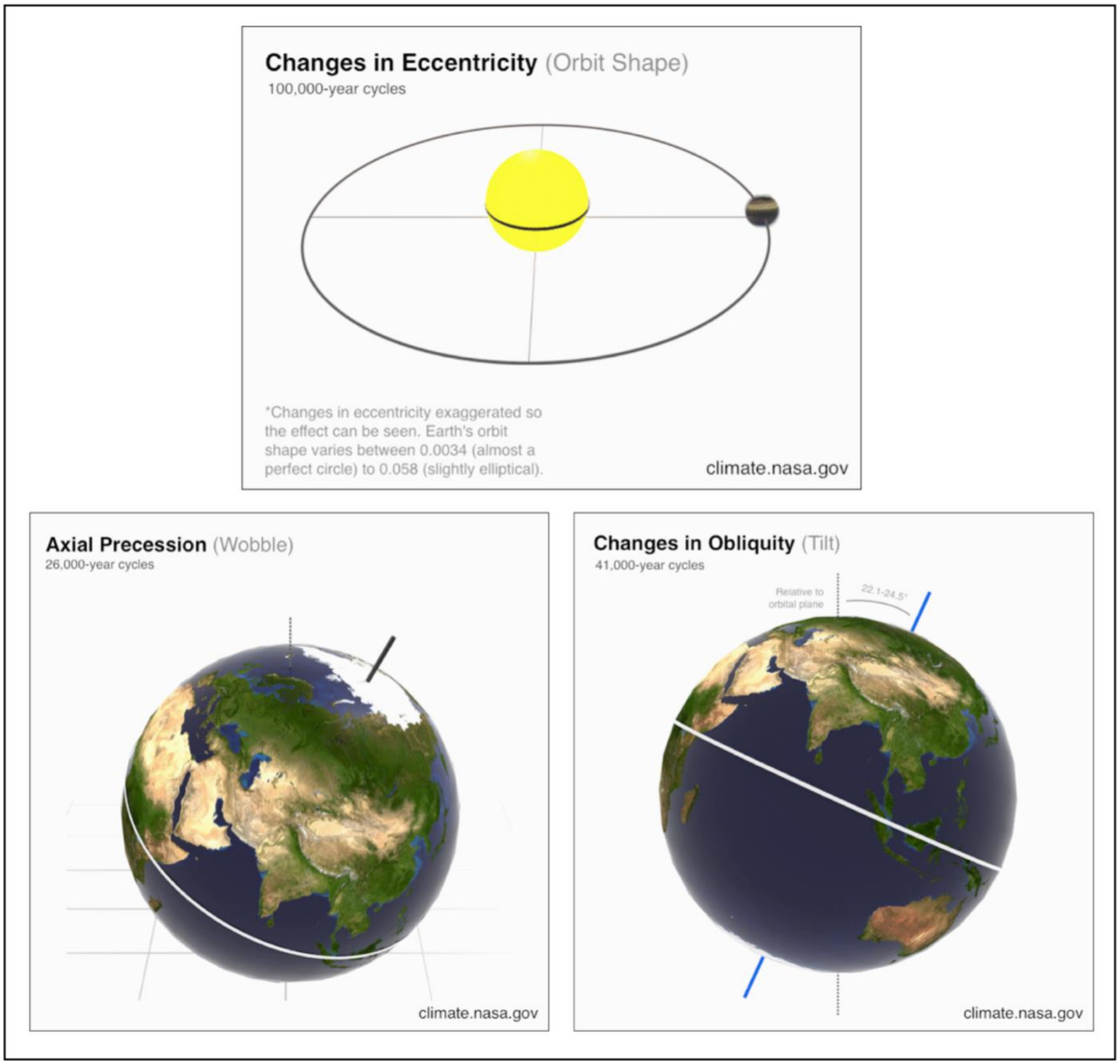


Figure 1.6: Milankovitch cycles, including the 1) shape of Earth's orbit, known as eccentricity; 2) angle Earth's axis is tilted with respect to Earth's orbital plane, known as obliquity; and 3) direction Earth's axis of rotation is pointed, known as precession.

Biogeochemical Cycles

A **biogeochemical cycle** is a pathway by which a chemical substance moves through biotic (biosphere) and abiotic (geosphere, atmosphere, and hydrosphere) compartments of Earth. These cycles include the carbon, nitrogen and sulfur, and phosphorus cycles.

Carbon Cycle

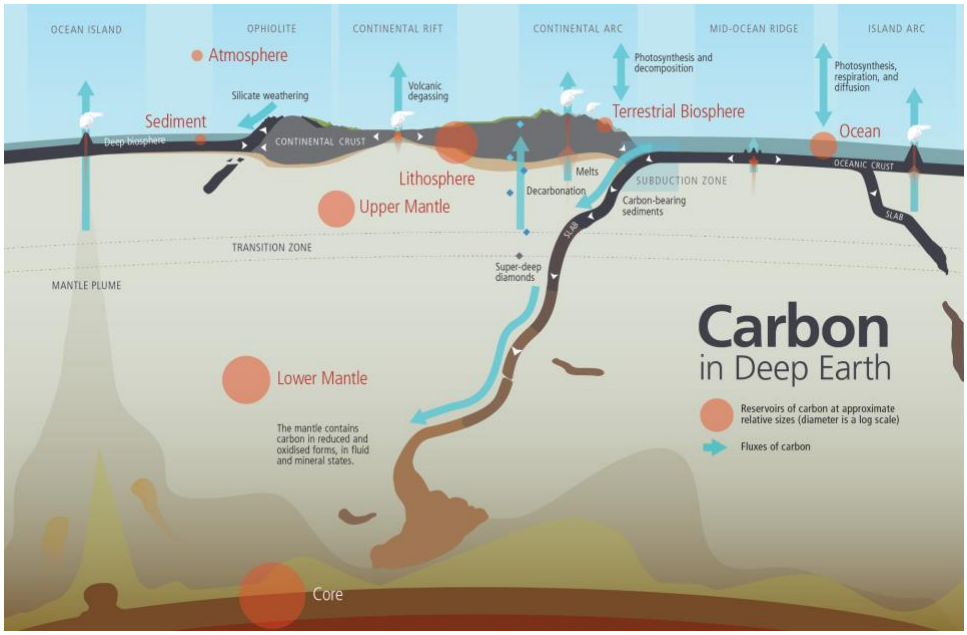


Figure 1.7: An overview of Earth's carbon reservoirs and the pathways between those reservoirs.

Nitrogen Cycle

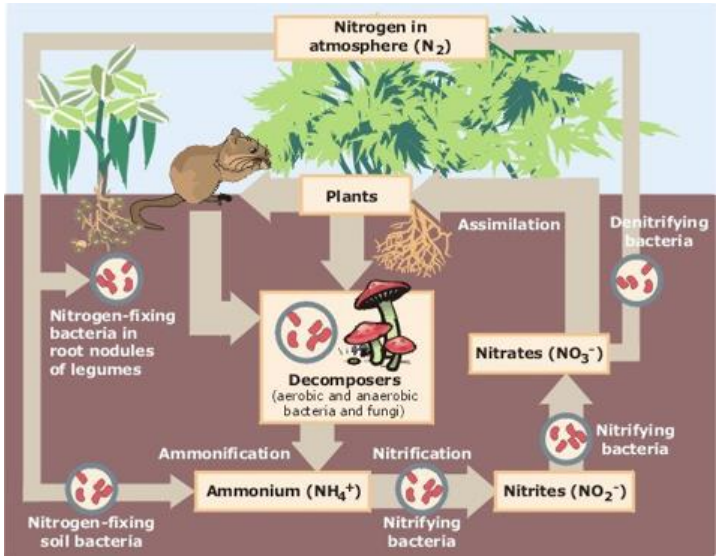


Figure 1.8: An overview of Earth's nitrogen reservoirs and the pathways between those reservoirs.

Sulfur Cycle

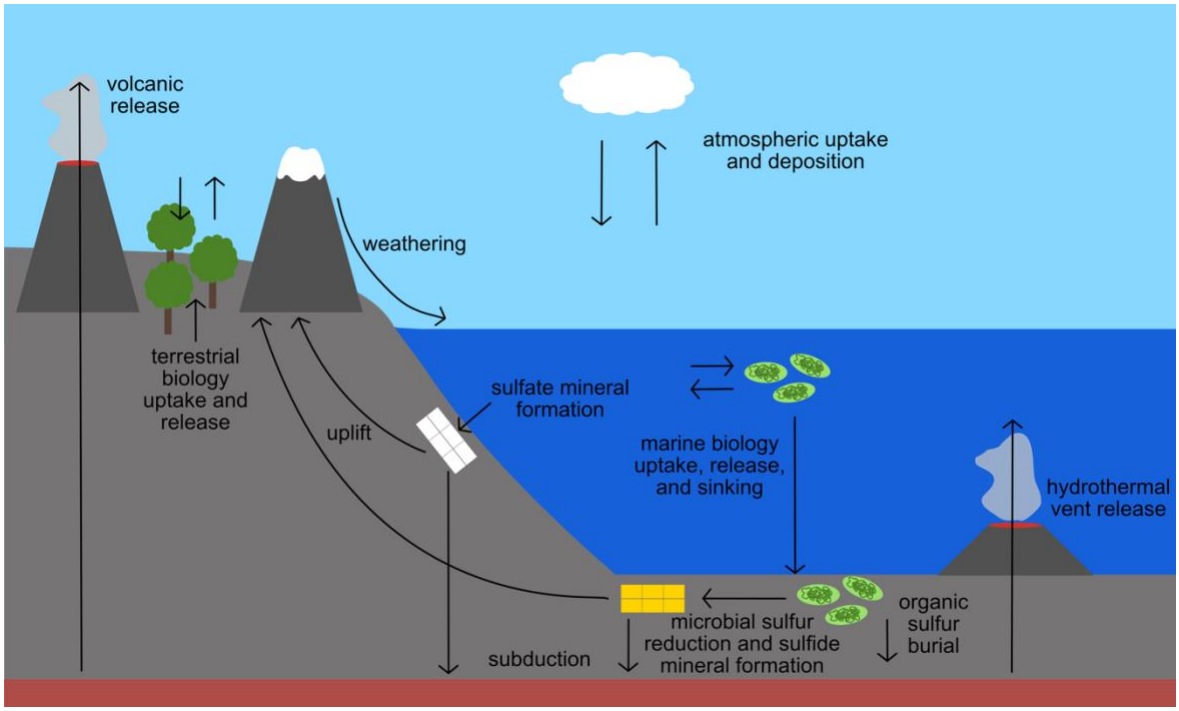


Figure 1.9: An overview of Earth's biogeochemical cycling of sulfur.

Phosphorus Cycle

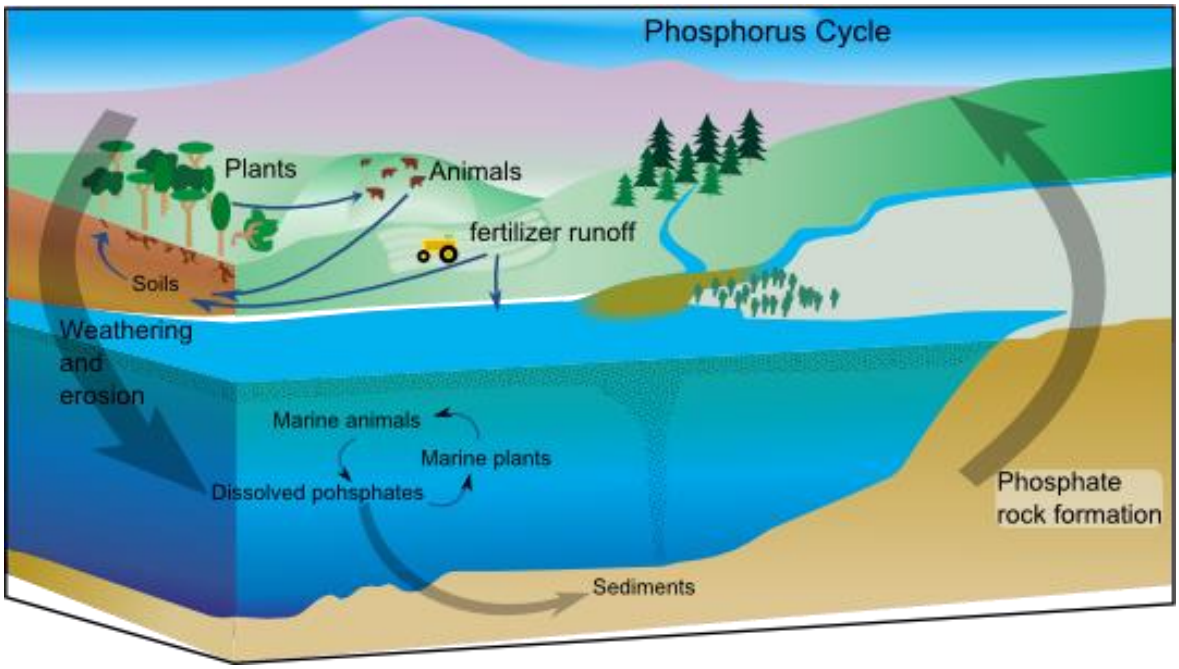


Figure 1.10: An overview of Earth's phosphorus reservoirs and the pathways between those reservoirs.

Attributions

- Figure 1.4: “The Water Cycle” (Public Domain; Howard Perlman and John Evans, USGS)
- Figure 1.5: Derivative of “Rock Cycle in Wilson Cycle” (CC-BY-SA 4.0; Fabirichter via Wikimedia Commons) by Chloe Branciforte.
- Figure 1.6: “Milankovitch Cycles and Their Role in Earth's Climate” (Public Domain; NASA/JPL-Caltech)
- Figure 1.7: “Carbon in Deep Earth” (CC-BY-SA 4.0; Mice of Mu via Wikimedia Commons)
- Figure 1.8: “Nitrogen Cycle” (Public Domain; EPA)
- Figure 1.9: “Sulfur Cycle” (CC-BY-SA 4.0; GeoscienceHd via Wikimedia Commons)
- Figure 1.10: “Phosphorus Cycle”; (CC-BY-SA 3.0; Bonniemf via Wikimedia Commons)

Activity 1D: Making Geological Observations

How Do Geologists Make Observations regarding Hand Samples or Specimens?

Recall that observations involve the five senses:

- sight (visual) - geologists will typically utilize a hand lens, magnifying glass, or microscope to see more detail.
- touch (kinesthetic)
- sound (auditory)
- smell (olfactory) - *waft the smell to your nose, like in a chemistry class.*
- taste (gustatory) - ***NEVER** taste an unknown sample.*

Always record any observations made. This ensures accuracy when you revisit your notes later.

1. To practice your observational skills, select a sample provided by your instructor. Document your observations in the table below.

Sample Number:	Observation	My Observation
	Visual	
	Feel	
	Smell	
	Sound	
	Taste	N/A; ***never*** taste an unknown sample.

How Do Geologists Categorize Specimens Based on Similar Observations?

Geologists frequently group similar samples together. Oftentimes, samples are grouped together based on observations about them. For this question, consider your sample and those of your classmates. Examine each sample and compare your observations.

2. To practice your categorization skills, develop categories for all the samples used in the previous question. Each category should contain more than one sample that shares some observable characteristic (i.e. color, feel, smell, etc.). For example, if you notice multiple samples are pink, place them all together in a "pink category". Use as many samples as necessary, however, it may not be possible to categorize all samples. Samples may exist in multiple categories.

Shared characteristic	Sample numbers included in this category

Activity 1E: Measurements in Geology

Observations and measurements are used in all of the sciences. An **observation** is information obtained directly from one of the five human senses. A **measurement** is a means of expressing an observation with great accuracy. Measurements are expressed by both a numerical value and a unit. It is critically important to always ensure your number has a unit! In the US, we use two systems to measure: the **English or Imperial System** and the **Metric or International System** **(SI)**. Typically, scientists will utilize the metric (SI) system for consistency.

Common geologic measurements

- **Length**: the distance between two points
- **Mass**: the amount of matter in an object
- **Time**: the duration of the event being observed
- **Temperature**: a measure of kinetic energy, commonly known as heat.

If you are unfamiliar with measurement abbreviations, the following tables may be a helpful reference.

Imperial System Abbreviations		**Metric System Abbreviations**	
Abbreviation	**Measurement**	**Abbreviation**	**Measurement**
--	--	mm	millimeter
in	inch	cm	centimeter
ft	feet	m	meter
mi	mile	km	kilometer
°F	Fahrenheit	°C	Celsius

Table 1.1: Abbreviations for common Imperial and Metric measurements.

Measurement conversions are an important part of the sciences. If you struggle with math, remember, ***you are better than math***! Math is a skill to learn, in the same way you learned to read and write. Like learning a language, it takes consistent practice to become fluent. The internet contains a wealth of information -- good, bad, and ugly. You will likely find many conversion tools with a simple Google search; however, the process behind conversions is helpful to learn, particularly if you plan to enter a STEM-based field. Help on conversions is available here.

Occasionally you many encounter measurements reported in **scientific notation**. Scientific notation will contain exponents and is useful for measurements that are very small or

extremely large (**Table 1.2**).

Decimal notation	Scientific notation
2.0	2×10^{0}
300	3×10^{2}
4,321.768	4.321768×10^{3}
-53,000	-5.3×10^{4}
6,720,000,000	6.72×10^{9}
0.2	2×10^{-1}
987	9.87×10^{2}
0.00000000751	7.51×10^{-9}

Table 1.2: Scientific notation equivalents for numbers written in decimal notation.

When recording measurements, scientists will sometimes indicate **scientific error**. Errors are differences between observed values and what is true in nature. For measurements, scientists commonly consider both **accuracy** (how close a measurement is to the true or accepted value) and **precision** (how close measurements of the same item are to each other). Precision is always independent of accuracy (**Figure 1.11**). The best quality scientific observations are both accurate and precise.

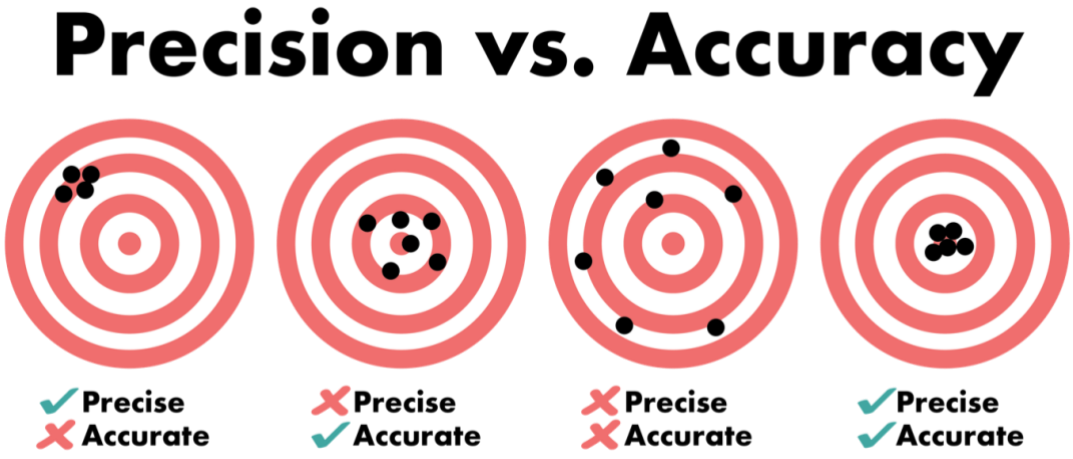


Figure 1.11: It is possible to be very precise but not very accurate, and it is also possible to be accurate without being precise. In this example, the closer the darts land to the bulls-eye, the more accurate they are.

What Is Rounding?

Rounding makes a number simpler but ensures it remains close to the original value. The rounded result is less accurate, but easier to use. This is why you should never round until you are ready to calculate the final answer. Your instructor will likely let you know to what place they would like you to round. So, how do you round numbers? First, identify which place value your instructor prefers you round to (whole number, tenth, hundredth, etc.); ask for clarification if you are unsure. Second, look to the next smallest place value, the digit to the right of the place value you're rounding to. If the digit in the next smallest place value is less than five, you leave the digit as-is. Any digits after that number (including the next smallest place value you just looked at) become zeros, or drop-off if they're located after the decimal point. This is **rounding down**. If the next smallest place value is greater than or equal to five (5, 6, 7, 8, or 9), you increase the value of the digit you're rounding to by one. Just like before, any remaining digits before the decimal point become zeros, and any that are after the decimal point are dropped. This is called **rounding up**.

For example, if we were to round 1.75 cm to the nearest tenth, the new value would become 1.8 cm. If we were asked to round 1.75 cm to the nearest whole number, the new value would become 2 cm.

1. Identify something that a geologist could measure.

2. How could a geologist make this measurement?

3. Why would measuring this be important?

4. Round 2.9785163 to the nearest hundredth.

5. Round 96.3452189 years to the nearest whole number.

6. Round 52.2176493 m to the nearest tenth.

7. Which is longer, an inch or a centimeter?

8. Which is longer, a meter or a yard?

9. Which is longer, a mile or kilometer?

10. Which is longer, an American football field or a soccer field?

11. Convert 10 kilometers to meters.

12. Convert 10 centimeters to meters.

13. Convert 10 meters to kilometers.

14. Convert 10 millimeters to centimeters.

15. Convert 16 miles to feet.

16. Convert 16 feet to miles.

17. Convert 16 feet to inches.

18. Convert 16 inches to feet.

Attributions

- Table 1.1: “Imperial vs. Metric” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 1.2: “Scientific Notation” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 1.11: “Precision vs. Accuracy” (CC-BY 4.0; Emily Haddad, own work)

Activity 1F: Taking Measurements

Qualitative Measurements

Sometimes in science, our measurements are qualitative rather than quantitative, yet are still extremely useful. For example, to identify minerals in the field, we can assess the mineral's hardness relative to common objects.

Test the hardness of the three mineral samples available by doing the following:

- try to scratch it with your fingernail.
- try to scratch glass with the mineral.

These two tests are listed in order of increasing hardness. For example, if you can scratch the mineral with your fingernail, it is very soft. If you can scratch the glass with the mineral, it is very hard. If your fingernail cannot scratch the mineral, and the glass cannot be scratched, the mineral has moderate hardness.

Your instructor will provide you with 3 minerals. Label the minerals in order of increasing hardness (soft, moderate, hard):

- Mineral A:
- Mineral B:
- Mineral C:

Quantitative Measurements

You will need the following equipment for these lab activities:

- Ruler.
- Calculator *(use a phone calculator or online calculator if necessary)*
- Additional practice on measurement

How to Measure Length

Using a ruler, measure the **length** of the line below in both centimeters and inches.

1. in centimeters:

2. in inches:

Locate a book, textbook, tissue box, or other similar-sized rectangular or square shaped object. Measure its length, width, and thickness (height) in both centimeters and inches.

	Measurement	*in centimeters*	*in inches*
3.	*Length:*		
4.	*Width:*		
5.	*Thickness (height):*		

How to Calculate Volume

To calculate volume, you must multiply the length by width by height. The proper units of volume are always measured in cubic units. The formula for volume is

Volume = Length * Width * Height

Calculate the volume of your selected object from above.

	Length	*Width*	*Height*	*Volume*
6.	*	*	=	(in cm^3)
7.	*	*	=	(in in^3)

Activity 1G: Measuring Angles

You will need the following equipment for these lab activities:

- Protractor; tutorial on how to use a protractor.
- 360 Protractor *(Note: both protractors can be printed. Print on transparency for best results.)*

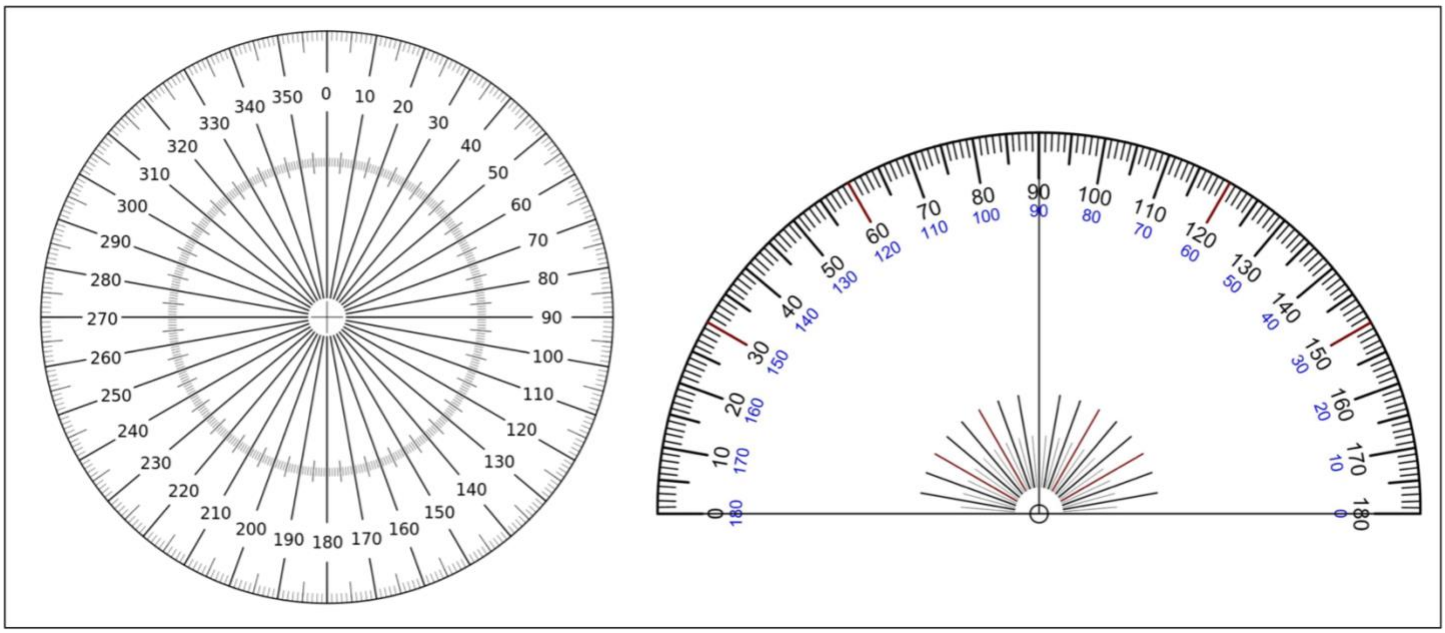
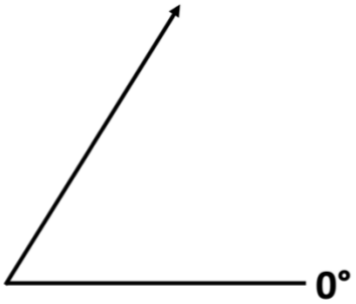


Figure 1.12: Protractor examples. A 360-degree protractor example is on the left, and a classic 180-degree protractor on the right. Both are commonly used for scientific purposes.

1. Using your protractor, measure the angle of the arrow below.



1.

Figure 1.13.1: An acute angle for measurement.

2. Using your protractor, measure the angle of the arrow below.

Figure 1.13.2: An acute angle for measurement.

3. Using your protractor, measure the angle of the arrow below.

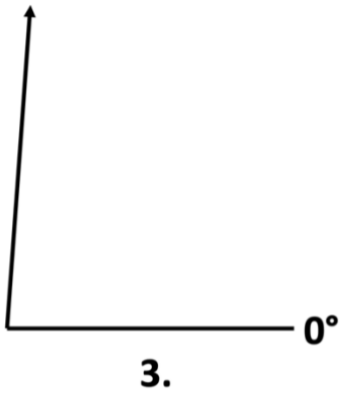


Figure 1.13.3: An acute angle for measurement.

4. Using your protractor, measure the angle of the arrow below.

Figure 1.13.4: An obtuse angle for measurement.

5. Below is a **compass rose**, which indicates the cardinal directions. North (N) is always represented as 0°/360°. On the compass below, label:
    a. The remaining cardinal directions (S, W, E) in **black.**
    b. The intermediate points (NE, SE, NW, SW) in **brown**.
    c. The intermediate points of the intermediate points (NNE, ENE, ESE, SSE, SSW, WSW, NNW, WNW) in **blue**.

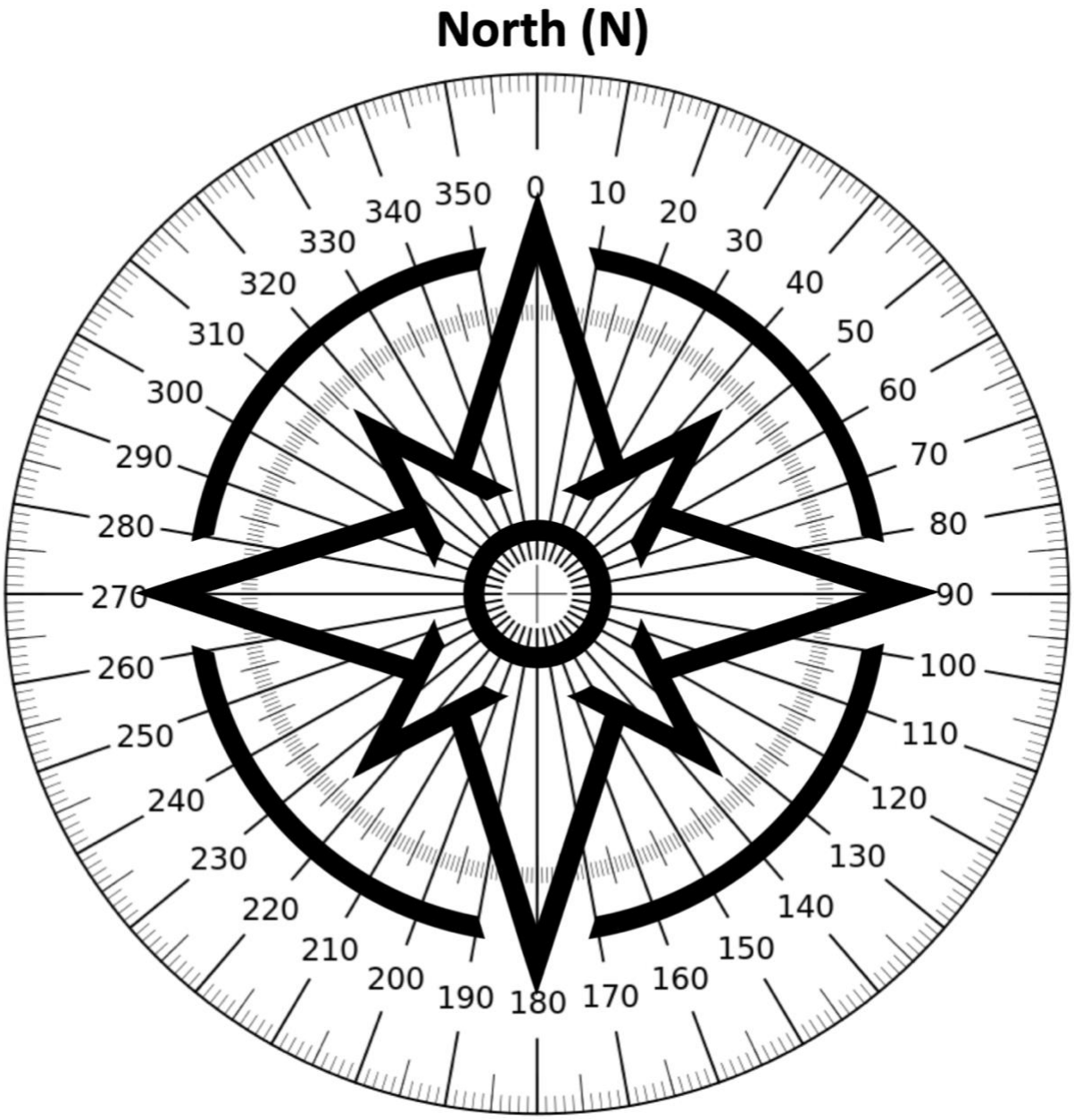


Figure 1.14: 360-degree protractor overlain with a standard compass rose; north is to the top of the page.

Attributions

- Figure 1.12: Derivative of Left: “Protractor Rapporteur Degree V1” (CC-BY-SA 3.0; Autiwa via Wikimedia Commons) and Right: “Rapporteur” (Public Domain; Scientif38 via Wikimedia Commons) by Chloe Branciforte
- Figure 1.13: “Angles for measurement” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 1.14: Derivative of “Protractor Rapporteur Degree V1” (CC-BY-SA 3.0; Autiwa via Wikimedia Commons) by Chloe Branciforte

Activity 1H: Rates of Change

One of the most important equations we will use in this course is the "dirt" equation:

Distance = Rate*Time (read as distance equals rate times time)

When you know two of the variables in this equation, you can figure out the third. We can move the variables around in the equation to suit our needs (but then we couldn't call it the "dirt" equation):

Rate = Distance/Time (read as rate equals distance divided by time)
or
Time = Distance/Rate (time equals distance divided by rate)

Example: Car Speed

It's summertime: you decide to go on a road trip. You want to figure out how long it will take you to drive to the **Grand Canyon**. You look on your map app and see that you are 380 miles away... when suddenly, your phone dies! Assuming you will drive at an average rate of 60 mph, how many hours will it take you to drive to the Grand Canyon?

First, write down your known variables:

Distance =

Rate =

Then, calculate your unknown variable using one of the equations above. Show your work:

Time =

Geology Example: Rate of Sedimentation

While you're out hiking, you encounter an interesting-looking **rock bed**. You can tell by the pebbles incorporated throughout the rock bed that it was laid down by a river over a long time. You want to find out how fast the bed was deposited by the river (this is called **rate of sedimentation**).

You measure how thick the bed is (this is its distance, a measurement of length) and discover it is 1.8 meters from the base to the top. Luckily, this bed is sandwiched by two ash beds laid down by volcanic eruptions: ash can be dated by radiometric dating!

After analyzing the samples in a lab, you learn the lower ash bed is dated at 10.1278 Ma (read as million years old) and the upper ash bed is dated at 10.1251 Ma.

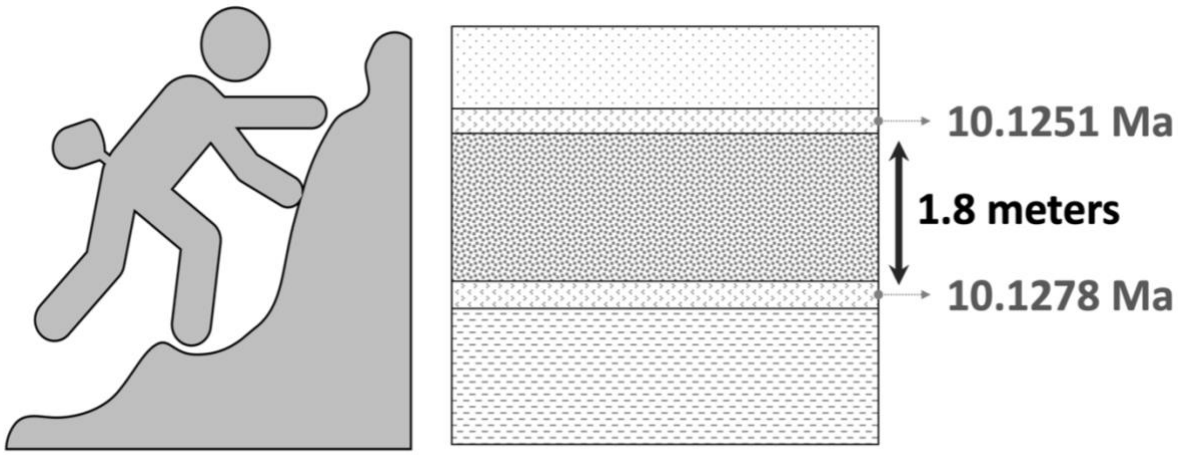


Figure 1.15: Outcrop of layers of sedimentary rock and ash. The ash layers have been radiometrically dated.

What is the average rate of sediment deposition for your rock bed?

Write down your known variables:

Distance =

Time =

Then, calculate your unknown variable. Show your work:

Rate =

Attributions

- Figure 1.15: “Outcrop of rock” (CC-BY 4.0; Chloe Branciforte, own work)

Chapter 2: Imagery and Maps in the Geosciences

Learning Outcomes

After completing this chapter, you should be able to:

- ✓ Describe and identify geoscience imagery.
- ✓ Interpret a topographic map, including contour lines.
- ✓ Determine the latitude and longitude of a point, location, etc.
- ✓ Interpret topographic profiles.

Thumbnail for Chapter 2:

Thumbnail: "NASA Satellites See California"; (CC-BY 2.0; NASA Goddard Space Flight Center via https://www.flickr.com/photos/24662369@N07/36967829824)

How Do Geoscientists View the Earth?

There are many ways to image or view Earth. The most obvious way is to go outside and hike around in person, but that may not always be an option. **Field work** is one of many ways in which a geologist can investigate a particular location (**Figure 2.1**). Field work focuses on specific questions, requires extensive planning and preparation, and is often expensive. Therefore, any research that can be done in a laboratory or office in advance, such as, collecting imagery, is helpful in shortening the time in the field and reducing the cost. When representing the surface and sub-surface of Earth, geologists use aerial, landsat, or DEM imagery, or a variety of maps, including topographic and geologic maps.

Figure 2.1: Field work examples. Clockwise, from left: Michael in Antarctica; Jen examining petrified wood in Petrified Forest National Park; Angelica sampling water; Tari examining core trays; Carina examining in the lab; Meghomita making measurements at an outcrop.

Can You Dig It?

Field work has evolved significantly during the centuries. Initially geologists were only able to rely on themselves to get to an area, usually by hiking, horseback, pack mule or boats. With the introduction of motorized transport, including trains, cars, and planes areas farther away became much easier to study. Technology has continued to be an important driving factor of field work evolution.

*The phrase "I'm going to do field work" has expanded to include both work outdoors AND in the laboratory, whether with test tubes and beakers or coding and KMZ files. For many geology undergraduates, field work, in its many forms, is a fundamental component of their curriculum. For us, **Google Earth** ensures everyone is able to participate and is afforded the same opportunity.*

All geoscientists use imagery, from paper maps to those generated via computer -- regardless of their discipline. Many are employed by universities, where they teach and/or do research, and state and federal agencies, including geological surveys like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways include environmental policy and legislation and consulting, or science communication via the private sector or state and federal agencies. Many of these career options require a college degree and postgraduate work. If you are interested in geoscience talk to your geology instructor for advice. We recommend completing as many math and science courses as possible. Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 2.1: “Geoscientists in the Field” (CC-BY 4.0; Chloe Branciforte, own work)

Aerial Imagery

Aerial images are photographs taken from an aircraft, helicopter, airplane, blimp, or other flying object, like a drone (**Figure 2.2**). These photographs are typically taken by mounted cameras or by hand by the photographer. Next time you fly, sit by the window and snap a photograph of the ground below! There are many different types of aerial imagery including: an **oblique aerial photograph**, which are photographs taken at an angle; and **vertical photographs**, which are taken straight down. The earliest surviving aerial image is from the late 1800's. Drones and other popular camera equipment continue to make access to these types of photos easy and quick, and relatively inexpensive.

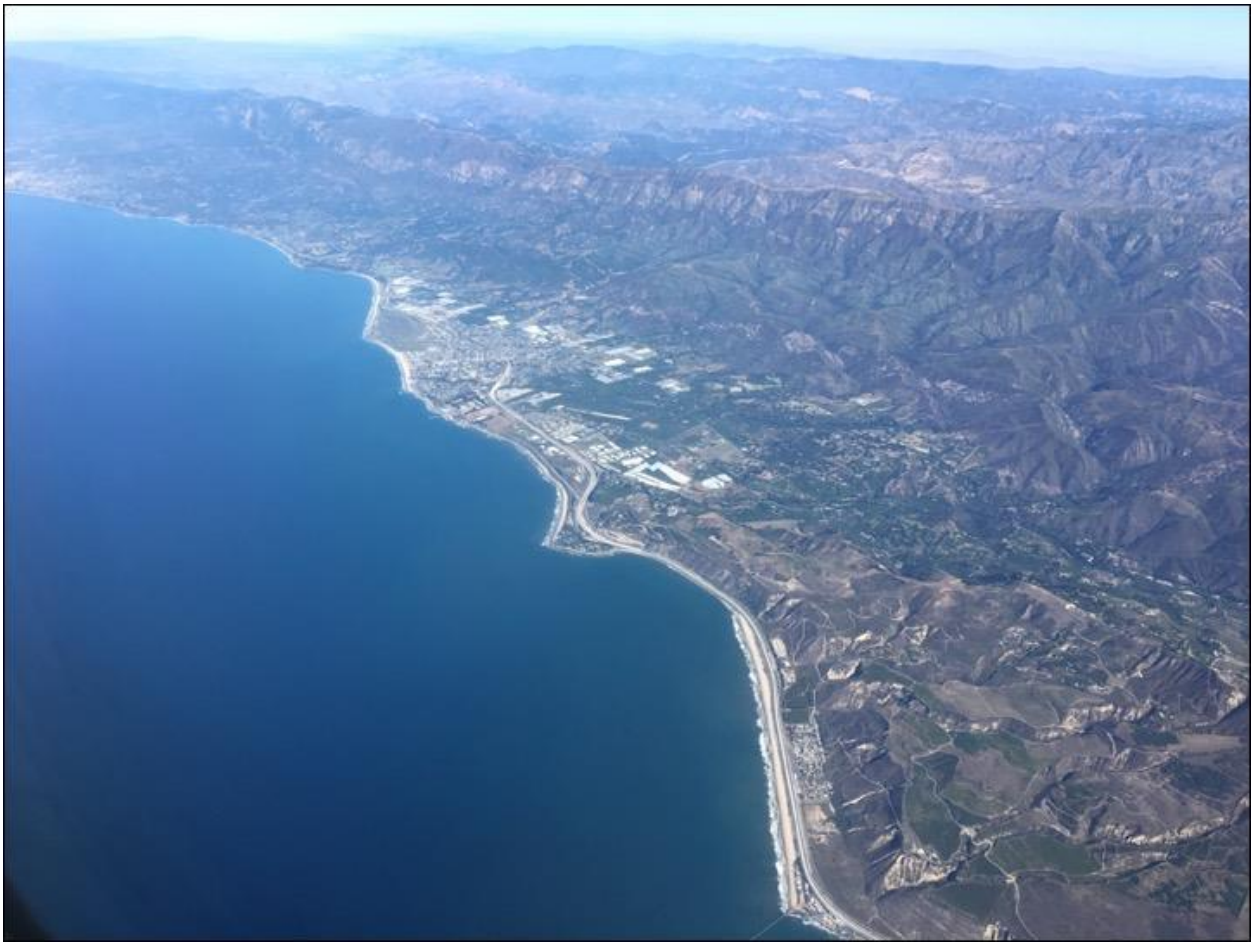


Figure 2.2: The Rincon near Carpinteria in Southern California.

Attributions

- Figure 2.2: “The Rincon in Southern California” (CC-BY 4.0; Matthew Sauter, own work)

Satellite Imagery

Satellite images are pictures of Earth or other solar system bodies collected by imaging satellites operated by governments and businesses around the world. Here in the US, all satellite images produced by NASA are published by NASA Earth Observatory and are freely available to the public (**Figure 2.3**). The first images taken from space were done in the 1940's and the first satellite photograph was taken in 1959. In 1972, one of the most famous space photos, "*The Blue Marble*" was taken. This coincided with the beginning of the **Landsat program** here in the US, which is the largest program for acquisition of imagery of Earth from space.

Figure 2.3: NASA Satellites see California from space.

Attributions

- Figure 2.3: “NASA Satellites See California”; (CC-BY 2.0; NASA Goddard Space Flight Center via Flickr)

Digital Elevation Model (DEM)

A **digital elevation model (DEM)** is a 3D computer generated representation of the surface of Earth, planetary body, moon, asteroid, etc. (**Figure 2.4**). DEMs are commonly built using data collected by **remote sensing** techniques, but they may also be built from land surveying.

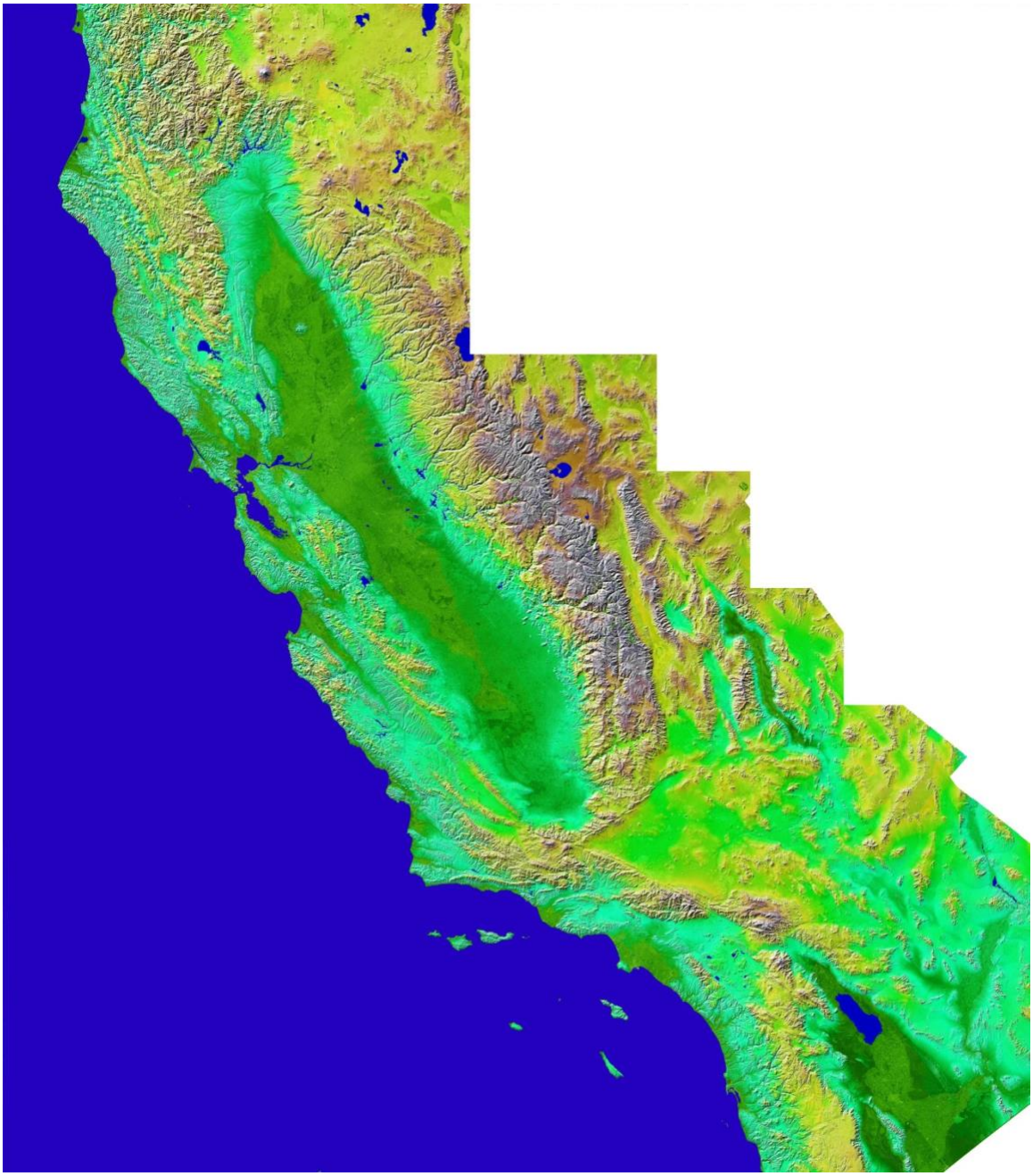


Figure 2.4: The diversity of landforms that make up the state of California. Color coding is directly related to topographic height, with blue and green at the lower elevations, rising through yellow and brown to white at the highest elevations.

Attributions

- Figure 2.4: “Shaded Relief with Color as Height, California Mosaic” (Public Domain; NASA/JPL/NIMA)

Topographic Maps

Maps were some of the first items used to represent the Earth, or a part of it. A topographic map represents **topography**, the shape and character of the Earth's surface, and depicts both natural and human-made features (**Figure 2.5**). This type of map uses **contour lines** to denote elevation, whereby each contour line connects points of equal elevation. Contours make it possible to measure the height of mountains, depths of the oceans, and steepness of slopes.

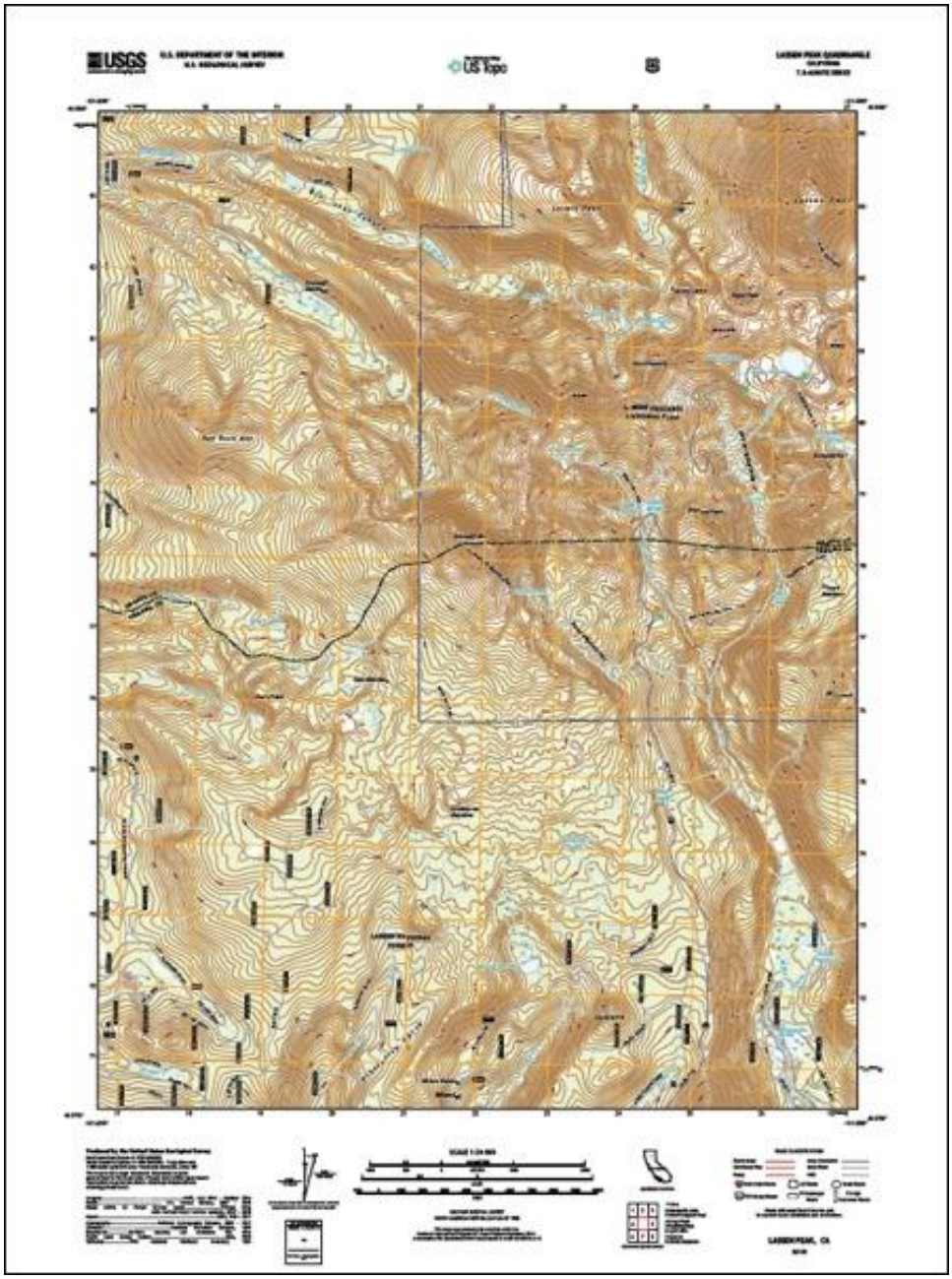


Figure 2.5: A topographic map of the Lassen Peak Quadrangle (2018).

Attributions

- Figure 2.5: “Lassen Peak Quadrangle” (Public Domain; USGS)

Map Reading Skills

Directions

Recall, cardinal directions are expressed as north (N), east (E), south (S), and west (W), with gradations in between, like northeast (NE), southwest (SW), north-northwest (NNW), etc. The most common way to describe direction is with a compass. The compass needle, which is magnetic, aligns itself with the Earth's magnetic north pole. A common misconception is that if you follow the north needle on a compass you will end up at the North Pole (hi polar bears!). In reality, the **magnetic north pole** is offset from the **geographic north pole** location, which we will discuss more in the plate tectonics chapter (**Figure 2.6**). On a topographic map there will always be a north arrow to indicate where north is. If there is not an arrow on the map, it is OK to assume north is to the top of the page.

Can You Dig It?

*Earth acts like a very large **bar magnet** with its south-seeking pole near the geographic North Pole. That is why the north needle of your compass is attracted toward the geographic north pole of Earth, because the magnetic pole that is near the geographic North Pole is actually a south magnetic pole! Confusion arises because the geographic term "North Pole" has come to be used (incorrectly) for the magnetic pole that is near the North Pole. Thus, "north magnetic pole" is actually a misnomer, it should be called the south magnetic pole.*

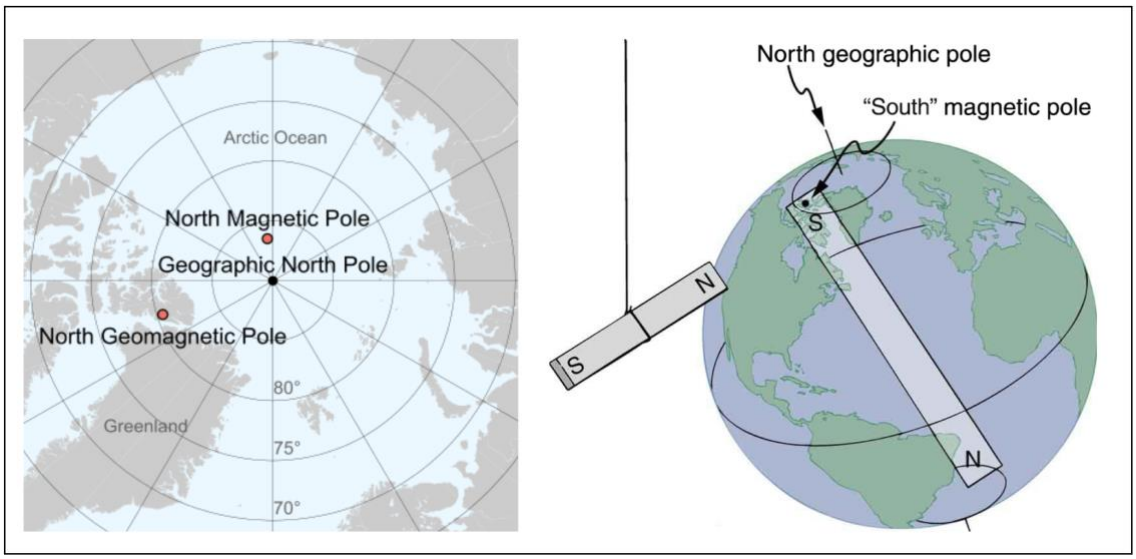


Figure 2.6: One end of a bar magnet is suspended from a thread that points toward north. The magnet's two poles are labeled N and S for north-seeking and south-seeking poles, respectively.

Magnetic Declination

Alongside the north arrow, there is usually an associated **magnetic declination**. The symbol for this is used in conjunction with a compass for navigational purposes. The star represents the direction of the geographic north pole or true north. The GN represents **grid north**, which is associated with the map projection, typically the Mercator projection. The MN represents the direction of magnetic north, the direction a compass needle would point (**Figure 2.7**). The magnetic declination will allow the map reader to determine where the map is located relative to geographic north. The direction of magnetic north varies both with position on the earth's surface and over time, therefore magnetic declination values on old maps may no longer be accurate. Magnetic declination values can be obtained from NOAA's National Centers for Environmental Information.

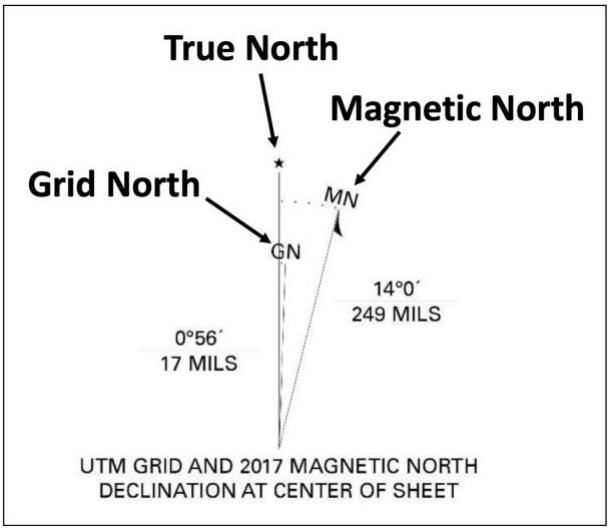


Figure 2.7: Magnetic North, True North, and Grid North of the Lassen Peak Quadrangle (2018).

Map Scales

Map scale is the relationship between distance on the map and distance on the ground. A **ratio scale** usually is given as a fraction or a ratio, for example 1/24,000 or 1:24,000 (**Figure 2.8**). The first number (map distance) is always 1. The second number (ground distance) is different for each scale; the larger the second number is, the smaller the scale of the map. These "representative fraction" scales mean that 1 unit of measurement on the map, 1 inch or 1 centimeter, represents 24,000 of the same units on the ground. The scale 1:24,000, states 1 centimeter on the map would represent 24,000 centimeters on the ground. The scale used for most US topographic mapping is 1:24,000. USGS maps at this scale cover an area measuring 7.5 minutes of latitude and 7.5 minutes of longitude and are commonly called **7.5- minute quadrangle maps**. A 7.5-minute quadrangle map covers an area of 49 to 70 square miles (130 to 180 km^2). Other common quadrangles may represent 15 minutes of latitude and longitude.

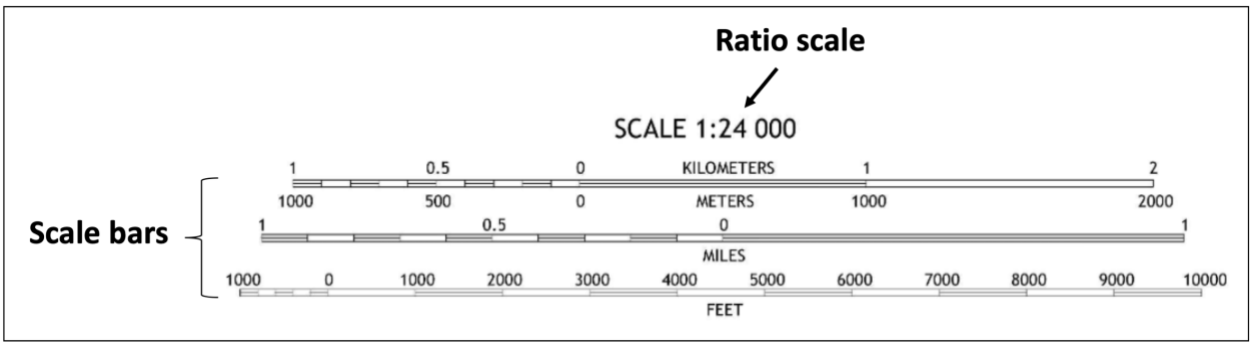


Figure 2.8: Scales for the Lassen Peak Quadrangle (2018).

Attributions

- Figure 2.6: Derivative of “North Magnetic Pole” (CC-BY 4.0; Cavit via Wikimedia Commons) and “Universal Characteristics of Magnets and Magnetic Poles” (CC-BY 4.0; OpenStax) by Chloe Branciforte
- Figure 2.7: Derivative of “Lassen Peak Quadrangle” (Public Domain; USGS) by Chloe Branciforte
- Figure 2.8: Derivative of “Lassen Peak Quadrangle” (Public Domain; USGS) by Chloe Branciforte

Latitude and Longitude

Latitude and longitude is a common **geographic coordinate system** which allows us to locate ourselves or other features on a map. It is used worldwide for navigational purposes on topographic maps, nautical maps, and road maps. It is also used in many GPS systems associated with phones, cars, boats, airplanes, military applications, firefighting, and tracking movement of tectonic plates, just to name a few. The latitude and longitude system is standardized so that a person from Mexico can easily communicate their location to a person in Africa or Europe, without any concern for potential language barriers.

Latitude, or parallels, represent how far north or south of the equator a point is on earth, measured in degrees, from 0° at the equator (00° 00' 00"), to 90° at the poles (**Figure 2.9**). Each degree is divided into 60 minutes ('), and each minute can be divided into 60 seconds ("). Lines of latitude remain the same distance apart as they circle the earth.

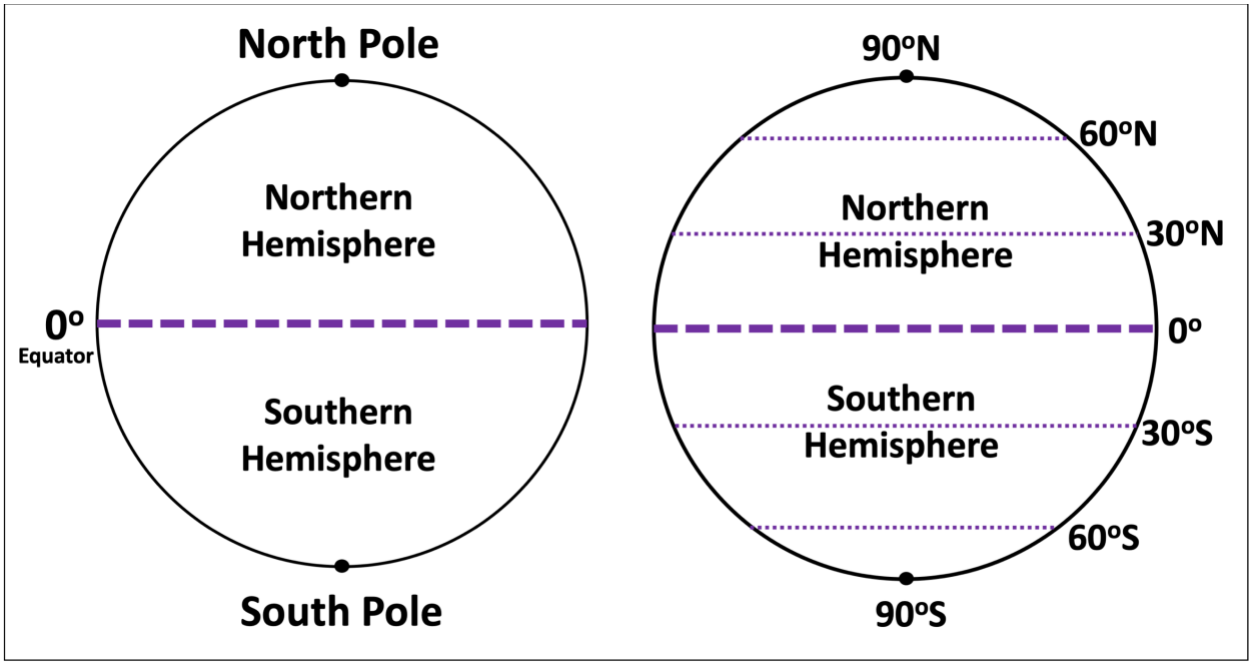


Figure 2.9: The equator divides the northern from the southern hemisphere. Additional lines of latitude are indicated.

When specifying a latitude, always state whether it is in the Northern Hemisphere (N) or Southern Hemisphere (S). For example, Half Dome in Yosemite National Park is located at 37° 44' 46" N latitude, read as 37 degrees, 44 minutes, and 46 seconds North latitude. This latitude does not locate Half Dome exactly, since this line of latitude encircles the entire globe north of the equator; we need to examine the other half of the coordinate system, longitude.

Longitude, or meridians, represent how far east or west a point on earth is from the Prime Meridian (up to 180°). The **Prime Meridian**, 0° 00', 00" longitude, is a north-south line that runs

through Greenwich, England. As they near the poles, lines of longitude become closer and closer together (**Figure 2.10**). Much like lines of latitude, each degree is divided into 60 minutes (‘), and each minute can be divided into 60 seconds (“).

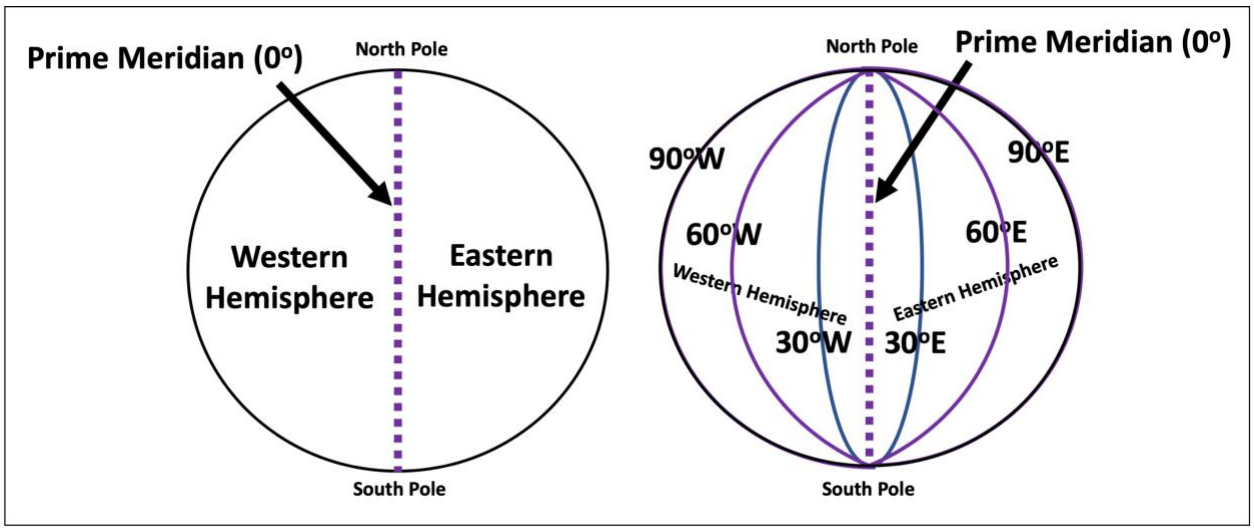


Figure 2.10: The Prime Meridian divides the eastern and western hemisphere. Additional lines of longitude are indicated.

When specifying a longitude, always state whether it is in the Western Hemisphere (W) or Eastern Hemisphere (E). For Half Dome, the longitude is 119° 32’ 4” W longitude, read as 119 degrees, 32 minutes, and 4 seconds West. Half Dome is in the Western Hemisphere, between the Prime Meridian in the east and the 180th meridian in the west. Note that the International Date Line (IDL), where the day changes, roughly corresponds to the 180th meridian.

Together, Half Dome can precisely be located at, 37° 44’ 46” N, 119° 32’ 4” W. In fact, if you were to copy and paste that coordinate in the browser version of Google Earth, you would fly directly to Half Dome. Go ahead and give it a try now!

Attributions

- Figure 2.9: “Lines of Latitude” (CC-BY 4.0; Chloe Branciforte and Cynthia Lampe, own work)
- Figure 2.10: “Lines of Longitude” (CC-BY 4.0; Chloe Branciforte and Cynthia Lampe, own work)

Universal Transverse Mercator (UTM)

UTM is another coordinate system that can be used to determine a location. It is most commonly used for military, research and survey applications. The UTM system divides the earth's surface into a grid. Each grid is identified by a number across the top called the zone number and a letter down the right hand side called the **zone designator** (Figure 2.11). For example: Los Angeles, CA is in UTM grid 11S.

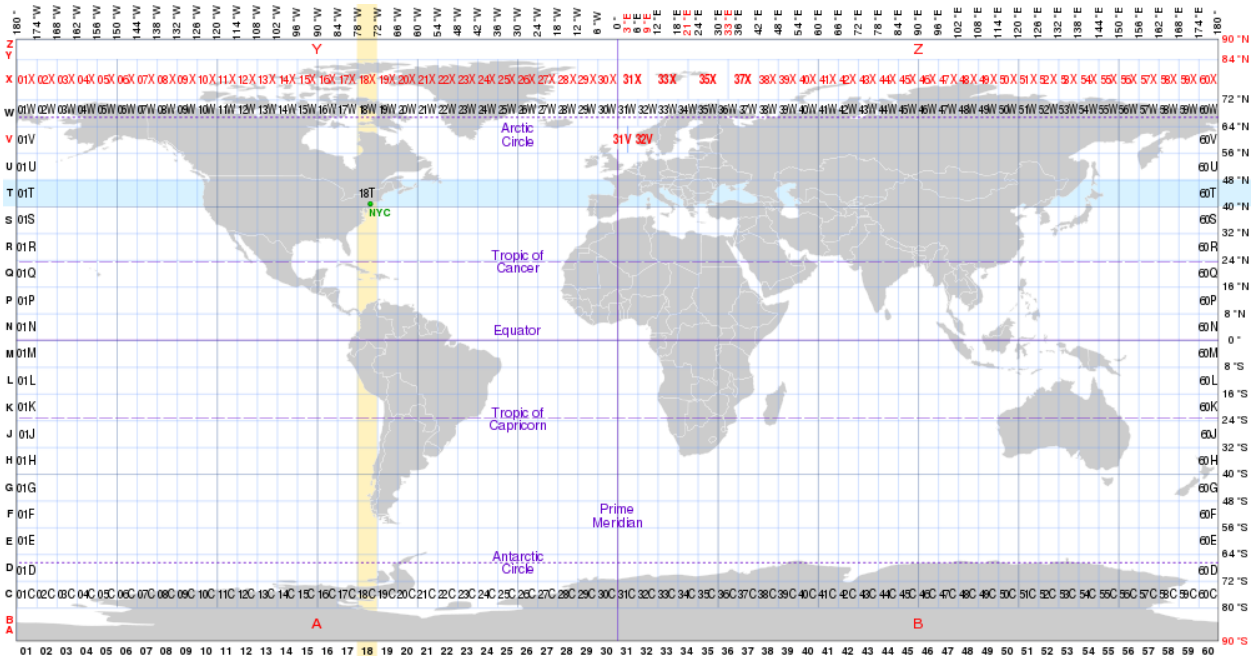


Figure 2.11: The Universal Transverse Mercator Grid.

Every spot within a zone can be defined by a coordinate system that uses meters. Your vertical position is defined in terms of meters north (**Northing**) and your horizontal position is given as meters east (**Easting**) shown in Figure 2.12. Along the borders of a topographic map you will find both latitude and longitude, and the northing and easting coordinates. The UTM coordinates can be identified by their unique formatting and mixture of font sizes.

Note that in Figure 2.12, the latitude and longitude are designated by positive and negative numbers, with a positive latitude indicating position in the northern hemisphere and a negative latitude indicating position in the southern hemisphere. Similarly, a positive longitude indicates the eastern hemisphere and a negative longitude represents the western hemisphere.)

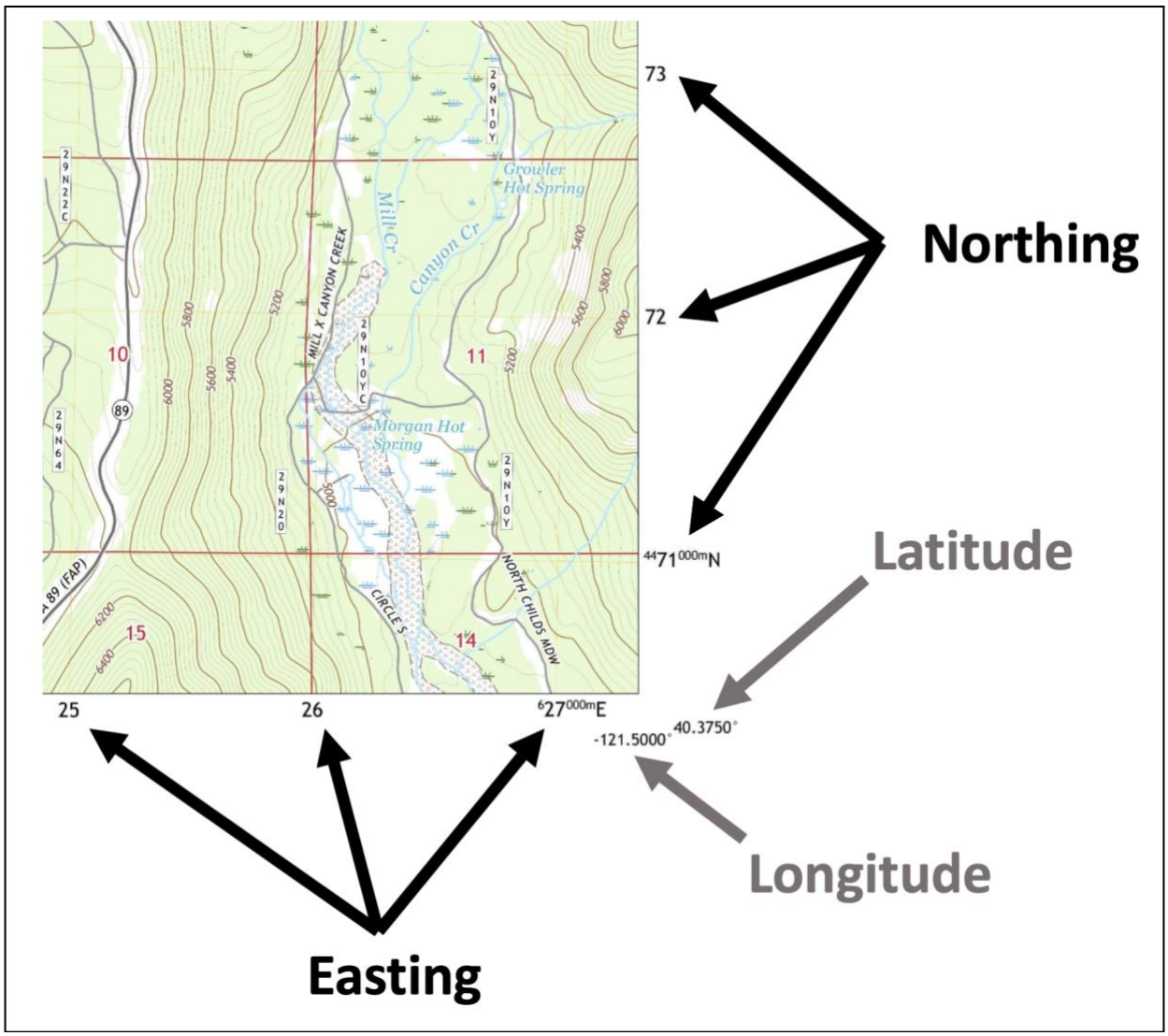


Figure 2.12: UTM, and latitude and longitude coordinate systems on the Lassen Peak Quadrangle (2018).

Attributions

- Figure 2.11: “Universal Transverse Mercator Zones” (CC-BY-SA 4.0; cmglee, STyx, Wikialine and Goran tex-en via Wikimedia Commons)
- Figure 2.12: Derivative of “Lassen Peak Quadrangle” (Public Domain; USGS) by Chloe Branciforte

How Do I Read a Topographic Map?

Topographic maps contain a significant amount of information, both within the map and along the margins. Before investigating a map, always look in the margins, including the area below the map, for information regarding title, location, scale and authorship (**Figure 2.13**).

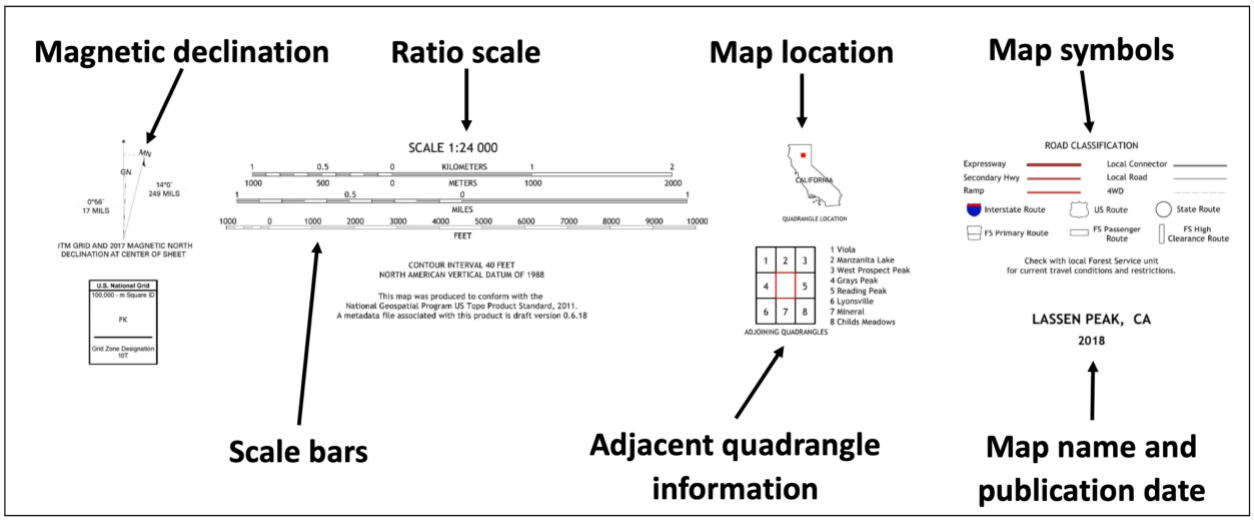


Figure 2.13: Bottom margin of a topographic map of the Lassen Peak Quadrangle (2018).

Many features on a topo map are shown by lines that may be straight, curved, solid, dashed, dotted, or in any combination. Topographic contours are shown in brown by lines of different widths. Each **contour** is a line of equal elevation; therefore, contours never cross. They show the general shape of the terrain. To help the user determine elevations, **index contours** are wider. Elevation values are printed in several places along these lines. The narrower intermediate and supplementary contours found between the index contours help to show more details of the land surface shape (**Figure 2.14**).

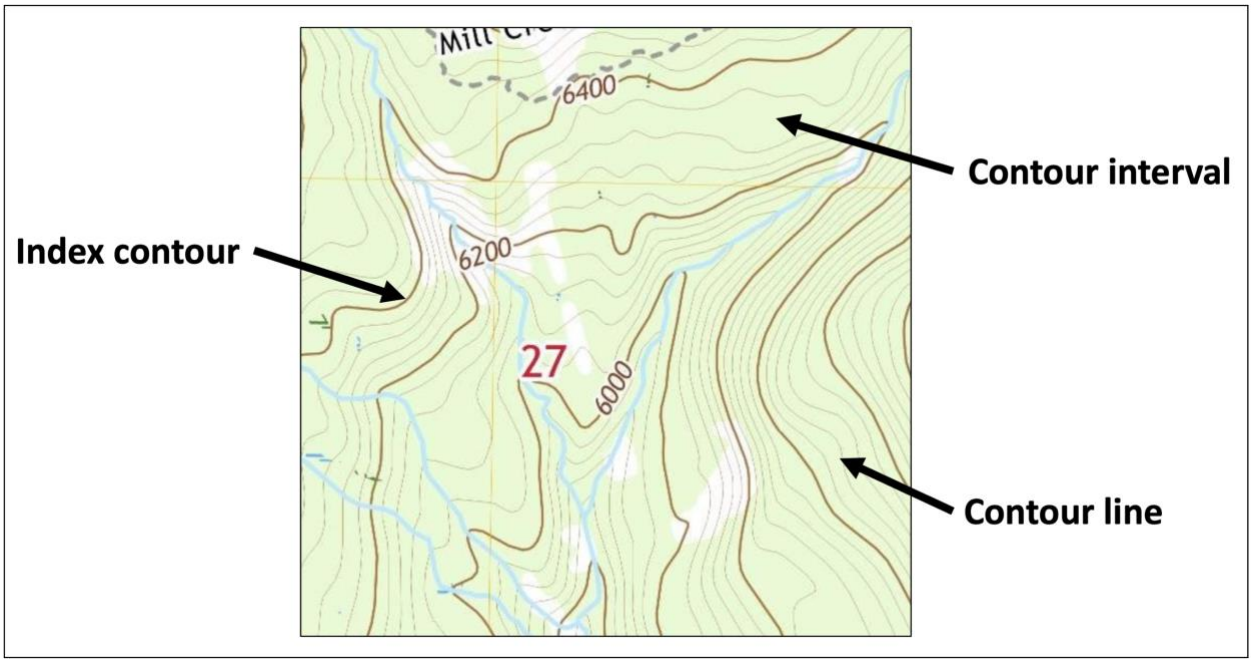


Figure 2.14: Contour interval, line and index contours for the Lassen Peak Quadrangle (2018).

Contours that are very close together represent steep slopes. Widely spaced contours or an absence of contours means that the ground slope is relatively level. The elevation difference between adjacent contour lines, called the **contour interval**, is selected to best show the general shape of the terrain. The contour interval is printed in the margin of each USGS map (**Figure 2.15**). Bathymetric contours are shown in blue or black, depending on their location. They show the shape and slope of the ocean bottom surface. The bathymetric contour interval may vary on each map and is explained in the map margin.

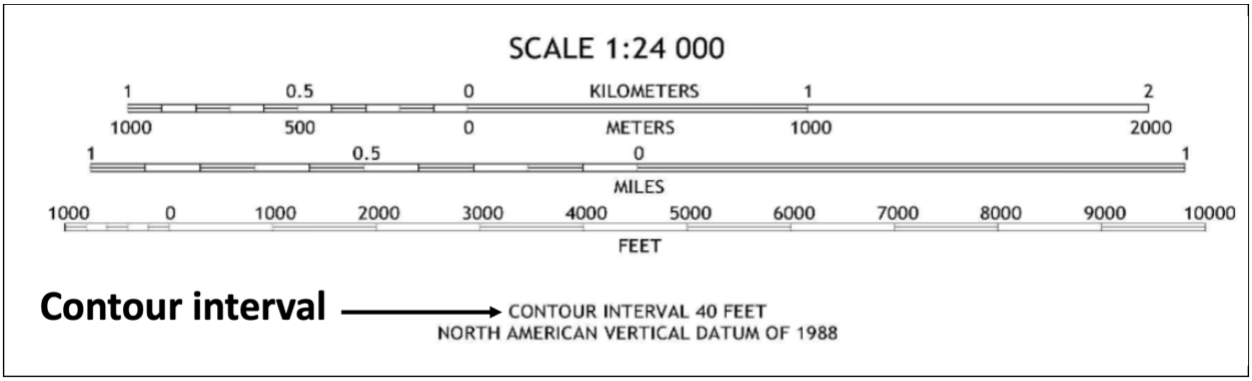


Figure 2.15: Contour interval for the Lassen Peak Quadrangle (2018).

Attributions

- Figure 2.13: Derivative of “Lassen Peak Quadrangle” (Public Domain; USGS) by Chloe Branciforte
- Figure 2.14: Derivative of “Lassen Peak Quadrangle” (Public Domain; USGS) by Chloe Branciforte
- Figure 2.15: Derivative of “Lassen Peak Quadrangle” (Public Domain; USGS) by Chloe Branciforte

Rules of Topographic Maps

- Contour lines connect points of equal elevation; therefore, every point along a contour line is the exact same elevation.
- Contour lines always separate points of higher elevation (uphill) from lower elevation (downhill).
- Contour lines never cross or intersect. A point on the surface of the earth cannot be at two different elevations. *An exception to this rule is, an overhanging cliff, and will be represented as dashed contour lines.*
- Contour lines never split or divide. *An exception to this rule is, a vertical cliff where contour lines appear to merge together, but are actually stacked on top of each other.*
- Contour lines always close to form a shape, usually an irregular circle. Note that sometimes contour lines extend beyond the area on a map so you may not see the entire closed circle (**Figure 2.16**).

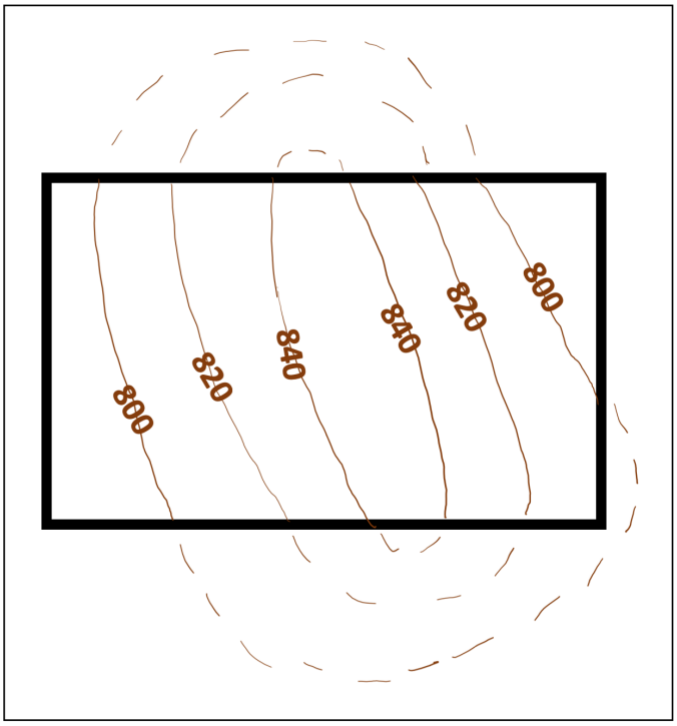


Figure 2.16: Close the contour shape or run the contours to the edge of the map.

- Closely spaced contour lines indicate a steeper slope. Contours which are further apart indicate a gentle slope (**Figure 2.17**).
- A hill is represented by a concentric series of closed contours (**Figure 2.17**). The "**rule of halves**" can be used to **interpolate** the high points: add half of the contour interval to the elevation of the highest contour line.

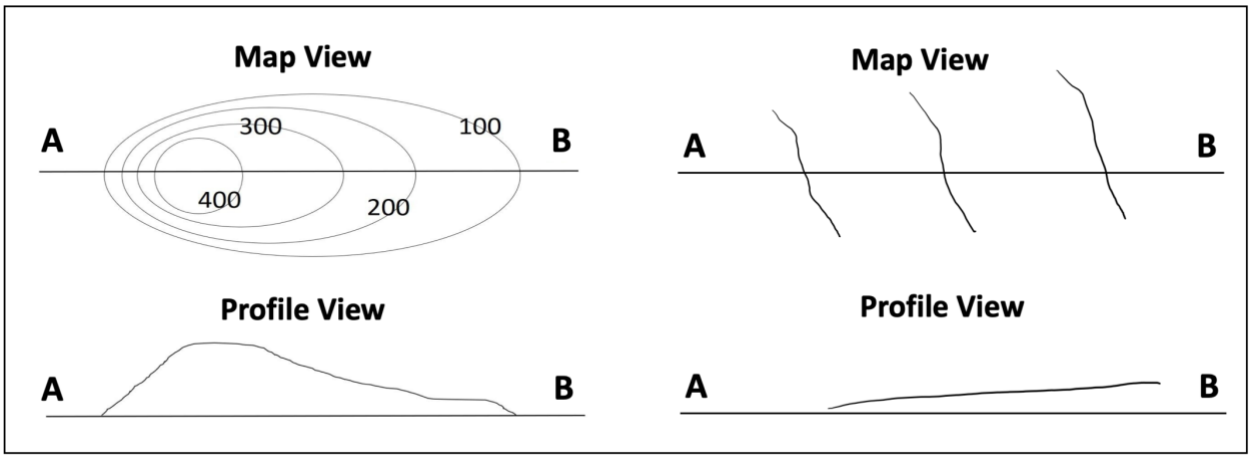


Figure 2.17: Contour lines which illustrate steep (left) vs. gentle (right) slope.

- Depression contours are indicated by hachure marks on the downhill side (**Figure 2.18**). The "rule of halves" can be used to interpolate the low points within craters: subtract half of the contour interval from the lowest depression contour.

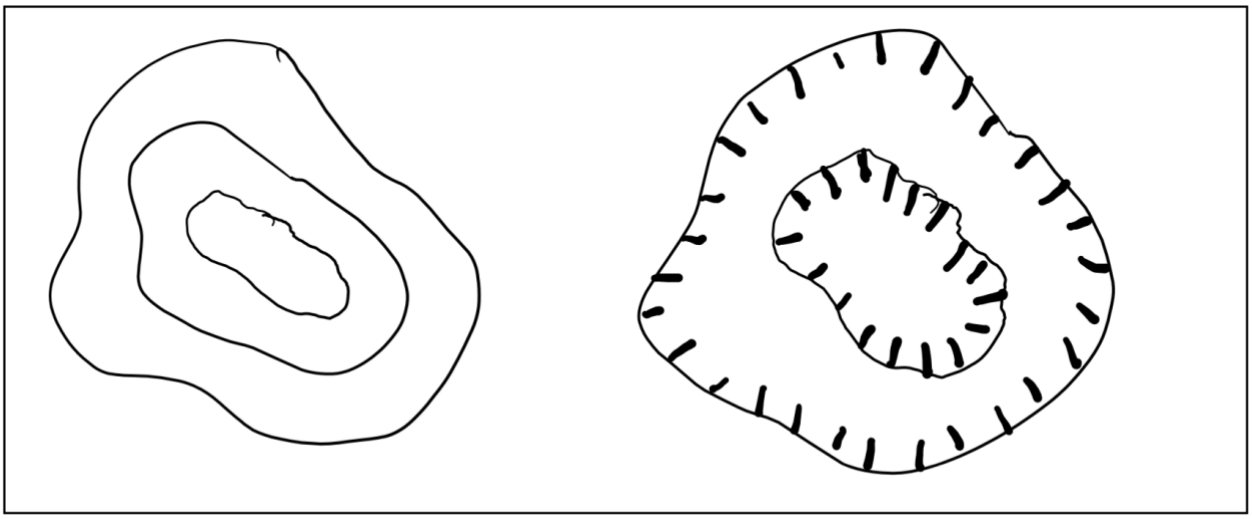


Figure 2.18: Left: Concentric series of closed contours represent a hill. Right: Concentric series of closed contours with hachure marks represent a depression.

- Contour lines "V" upstream when crossing a stream. The point of the "V" points uphill (**Figure 2.19**).

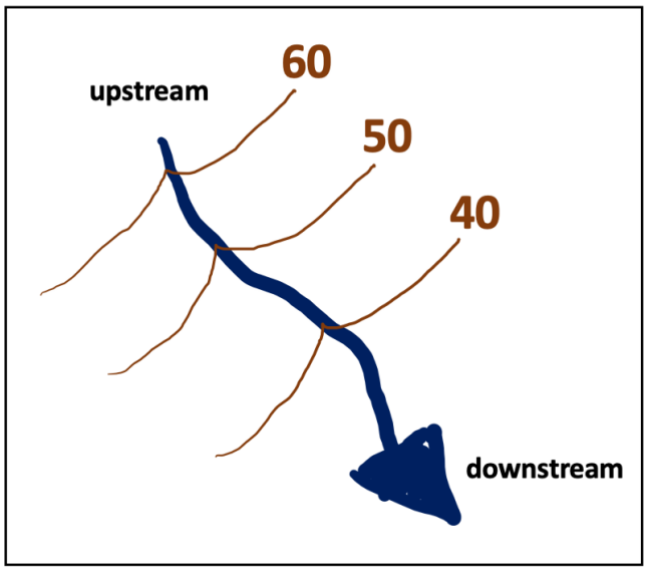


Figure 2.19: Contour lines “V” upstream, with the “V” pointing uphill.

Attributions

- Figure 2.16: “Closing a Shape” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 2.17: “Steep vs. Gentle Slope” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 2.18: “Hill vs. Depression in map-view” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 2.19: “Rule of V’s” (CC-BY 4.0; Chloe Branciforte, own work)

Topographic Map Legends and Symbology

Topographic map symbols represent features such as streets, buildings, streams, and vegetation. These symbols are often updated to improve the appearance or readability of the map. Here in the US, the United States Geological Survey (USGS) uses standard symbols across their maps, and will likely be important in this course.

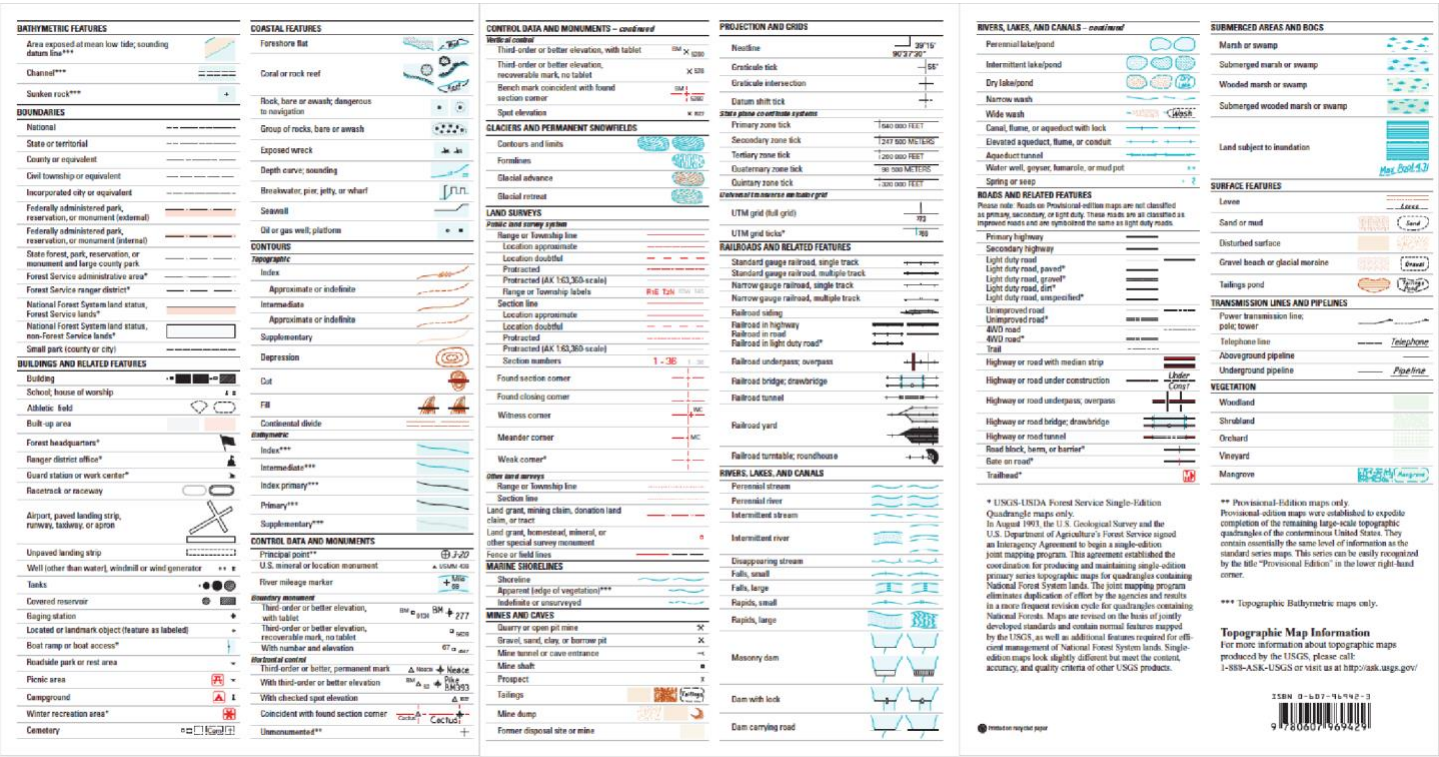


Figure 2.20: Topographic map symbols.

Attributions

- Figure 2.20: “Topographic map symbols” (Public Domain; USGS)

Determining Gradient

One of the most basic topographic observations that can be made is the **gradient**, or slope, of the ground surface. **High, or steep, gradients** occur in areas where there is a large change in elevation over a short distance. **Low, or gentle, gradient**s occur where there is little change in elevation over the same distance. Steep versus gentle are relative terms, meaning, what would be considered steep in some parts of the country might be considered gentle in another part. However, gradients can still be compared between different parts of a map. The gradient can be determined through interpretation of the contour line spacing. For example, contour lines that are very close together signify steep terrain, whereas contours lines that are further apart indicate a flatter land surface (**Figure 2.17**). Gradient can also be determined mathematically using the following formula:

(elevation of point A - elevation of point B) / (distance from point A to point B)

Gradient typically has units in feet per mile (ft/mi).

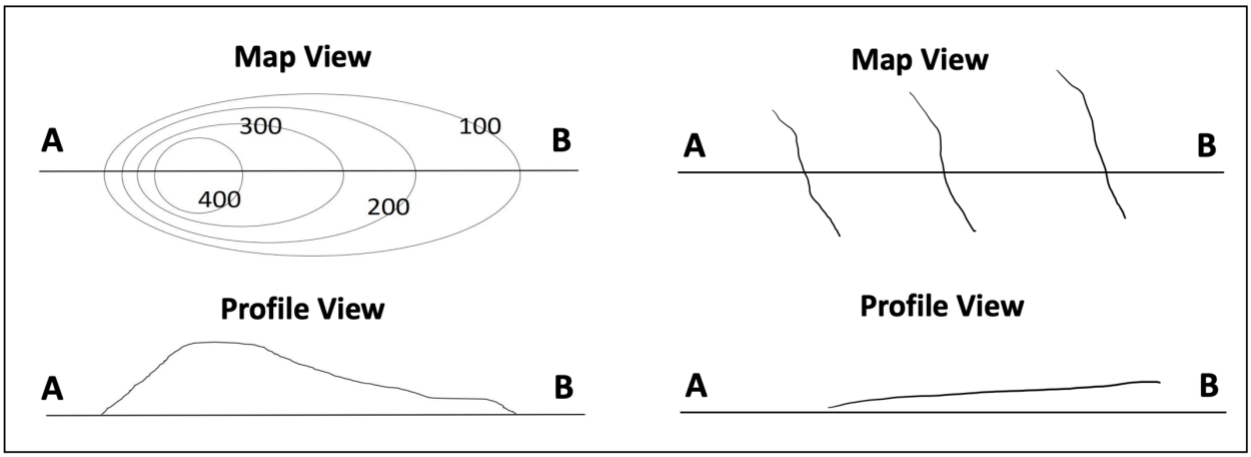


Figure 2.21: Contour lines which illustrate steep (left) vs. gentle (right) slope.

Attributions

- Figure 2.17: “Steep vs. Gentle Slope” (CC-BY 4.0; Chloe Branciforte, own work)

Topographic Profiles

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.

To successfully draw a topographic profile, follow these simple steps or visit How do I construct a Topographic Profile? for additional help.

1. Locate a line on a map that is interesting. In many cases, this line is given to you (often labeled A-A' or A-B). Grab a piece of blank paper and place the edge along this line. Mark the starting and ending points of the line. Be sure you label them appropriately, as A and A', or A and B, or however the original line on the map is identified.
2. Start at one end, for example the A end, and move along the edge of the paper, making a mark on the paper every time a contour line touches the edge of the paper. Make sure you label each mark with the right elevation so that you can transfer that point to the correct elevation on your profile. It is important to write neatly to ensure your labels can be read during a later step. Note the highest and lowest elevation.
3. Use a piece of graph paper (or horizontally lined paper) that is at least as long as your profile line. If needed, tape paper together to a long enough sheet; make sure the grid lines line up.
4. On the graph paper, draw a horizontal line the length of the profile line. Draw vertical lines above your starting and ending points. Label the y-axis (vertical lines) with elevation. It is important to consider the scale, using the noted highest and lowest elevations from Step 2. For example, if the lowest elevation is 7,200 feet and the highest is 10,600 feet, you'd likely want to label your axis from 7,000 to 11,000 feet.
5. Line up your original tick marked paper with the line drawn on your graph paper. Beginning with the elevation on the left-hand side of the paper, go directly up from that tick mark to make a small dot at the corresponding elevation. Note that the point does not need to be on a vertical line on the graph paper.
6. Once you have transferred all of your tick marks to your graph paper, connect the dots using a smooth curve. When connecting dots, recall you are interpreting the land surface between contour lines and therefore want smooth and consistent lines, and not straight lines. If you compare your profile with a fellow classmate, you may notice slight differences; overall, however, they should be a similar shape.

Activity 2A: Drawing Contour Lines

Follow these Rules for Drawing Contour Lines:

- Contour lines connect points with the ***same*** elevation.
- When drawing contour lines, connect the data points with ***one***, smooth line avoiding sharp angles.
- Contour lines never cross, branch off, or touch each other (there are exceptions).
- When contour lines cross streams they point towards the higher elevation.
- If a contour line is close to the perimeter of the map & does not form an enclosed circle, continue it to the edge of the map.
- Use a ***pencil*** to draw the contour lines and if you make a mistake, ***erase*** completely. You could also complete the map digitally.

Helpful tips:

- *Before you start drawing contours lines, note the location of the highest elevation, the lowest elevation, any water bodies, and the contour interval.*
- *It is usually easier to start with the contour line that has the lowest elevation.*
- *Only work on one contour line at a time!*

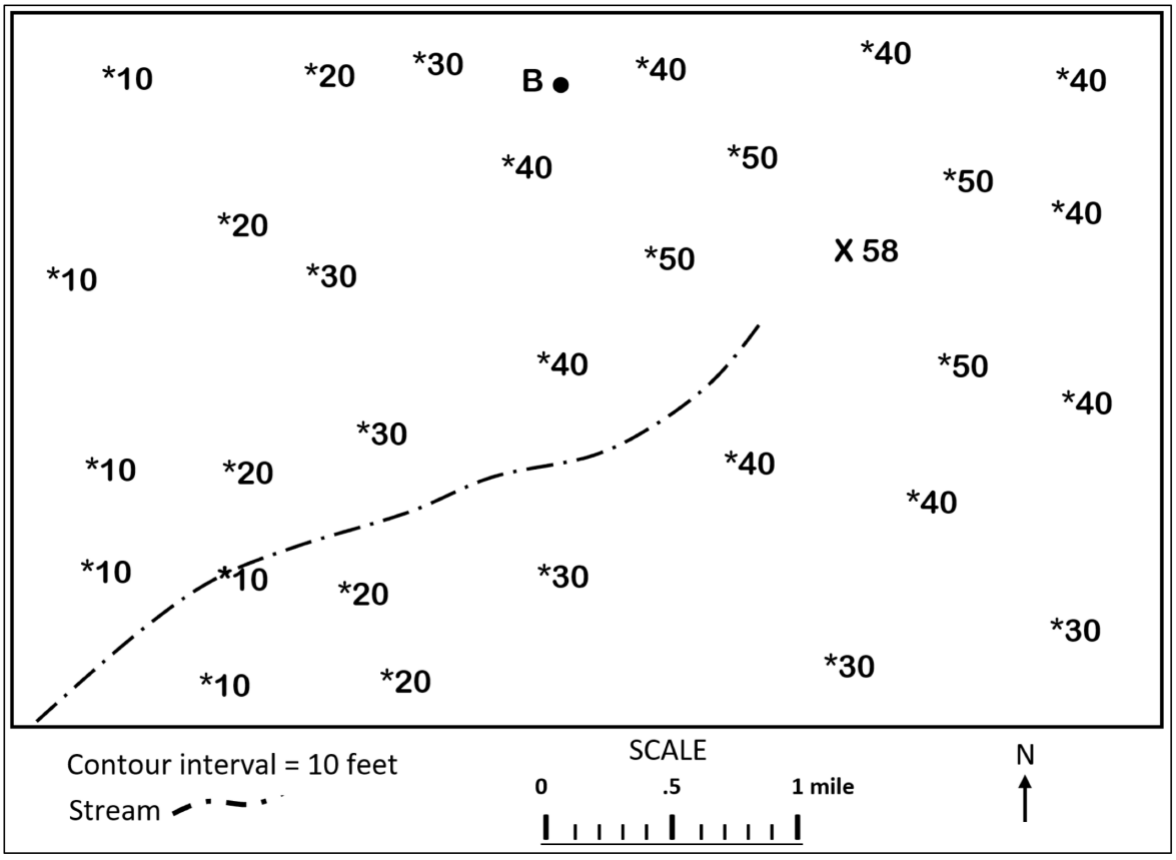


Figure 2.22: Elevation points to practice drawing contour lines.

1. With a **pencil (or digitally)**, draw in contour lines on **Figure 2.21** using a 10-foot contour interval.

2. Answer the following questions based on the contour map you have completed,

    a. In what **direction** does the stream flow?

    b. How were you able to determine the direction?

    c. What is the distance from the **highest hill** to point **B**. ?

    d. How were you able to determine point **B** is near a hill?

Attributions

- Figure 2.21: “Make Your Own Contour Map” (CC-BY 4.0; Cynthia Lampe, own work)

Activity 2B: Topographic Map of Death Valley National Park

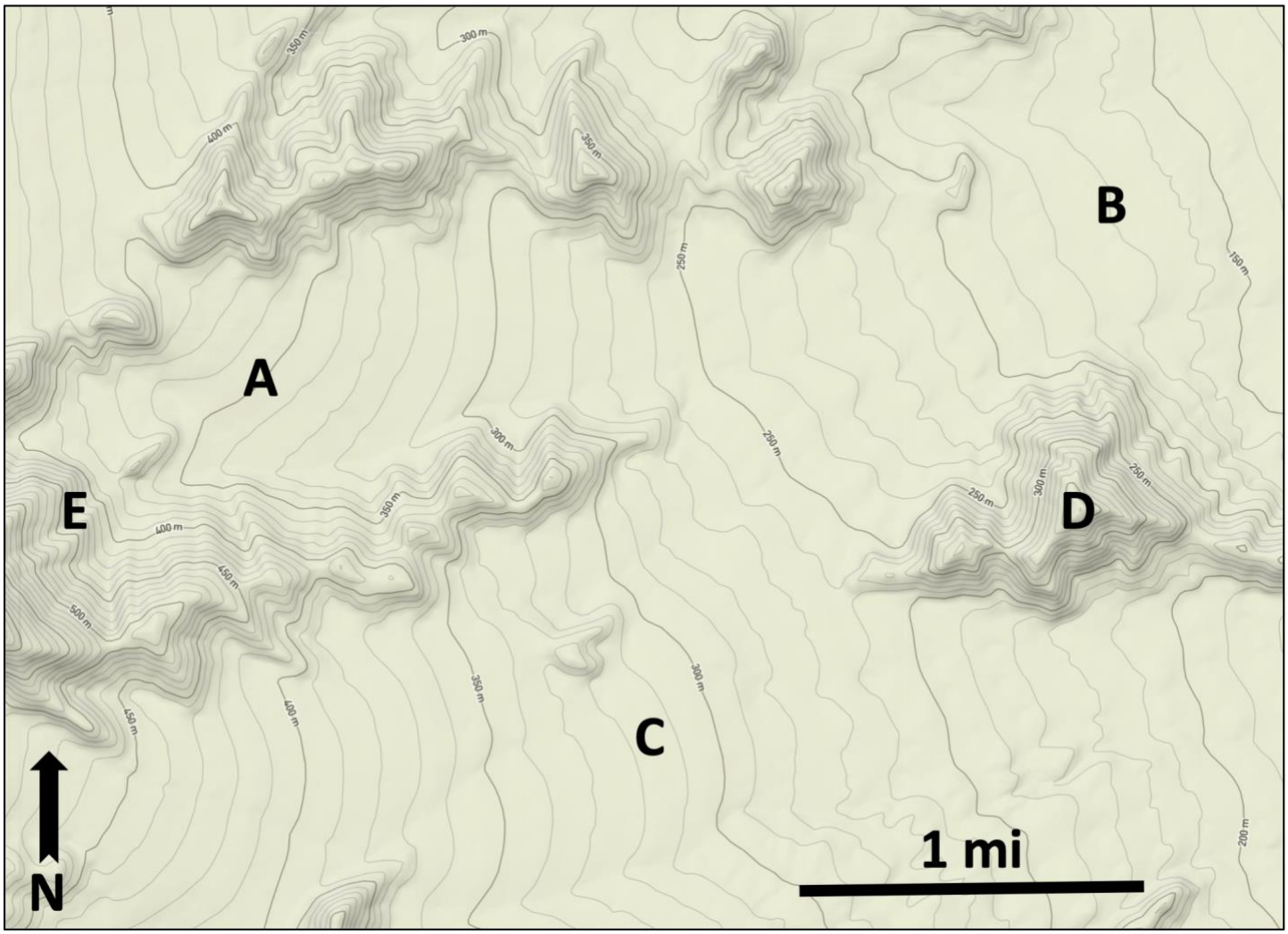


Figure 2.23: Topographic Map near Death Valley National Park.

1. Determine the contour interval of the map. *Show your work*.

2. What is the elevation at **Point B**?

3. Interpolate the elevation at **Point C**. *Hint: **interpolation** is the process of estimating an unknown value from neighboring known values*.

4. What is the elevation at **Point A**?

5. Could a person standing at **Point A** see their friend located at **Point C**, with the aid of high-power binoculars? Why or why not?

6. Could a person standing at **Point D** see their friend located at **Point B**, with the aid of high-power binoculars? Why or why not?

7. Which area on this map has the steepest slope?
    - **a.** A
    - **b.** B
    - **c.** C
    - **d.** E

8. How did you determine this?

9. Calculate the gradient from **Point A** to **Point B**, in feet per mile (feet/mile). *Hint: Use the scale bar to determine the distance from Point A to Point B. Show your work!*

Attributions

- Figure 2.22: Derivative of “Topographic Map near Death Valley National Park” (Public Domain, USGS) by Chloe Branciforte

Activity 2C: Reading a Topographic Map of Yosemite Valley

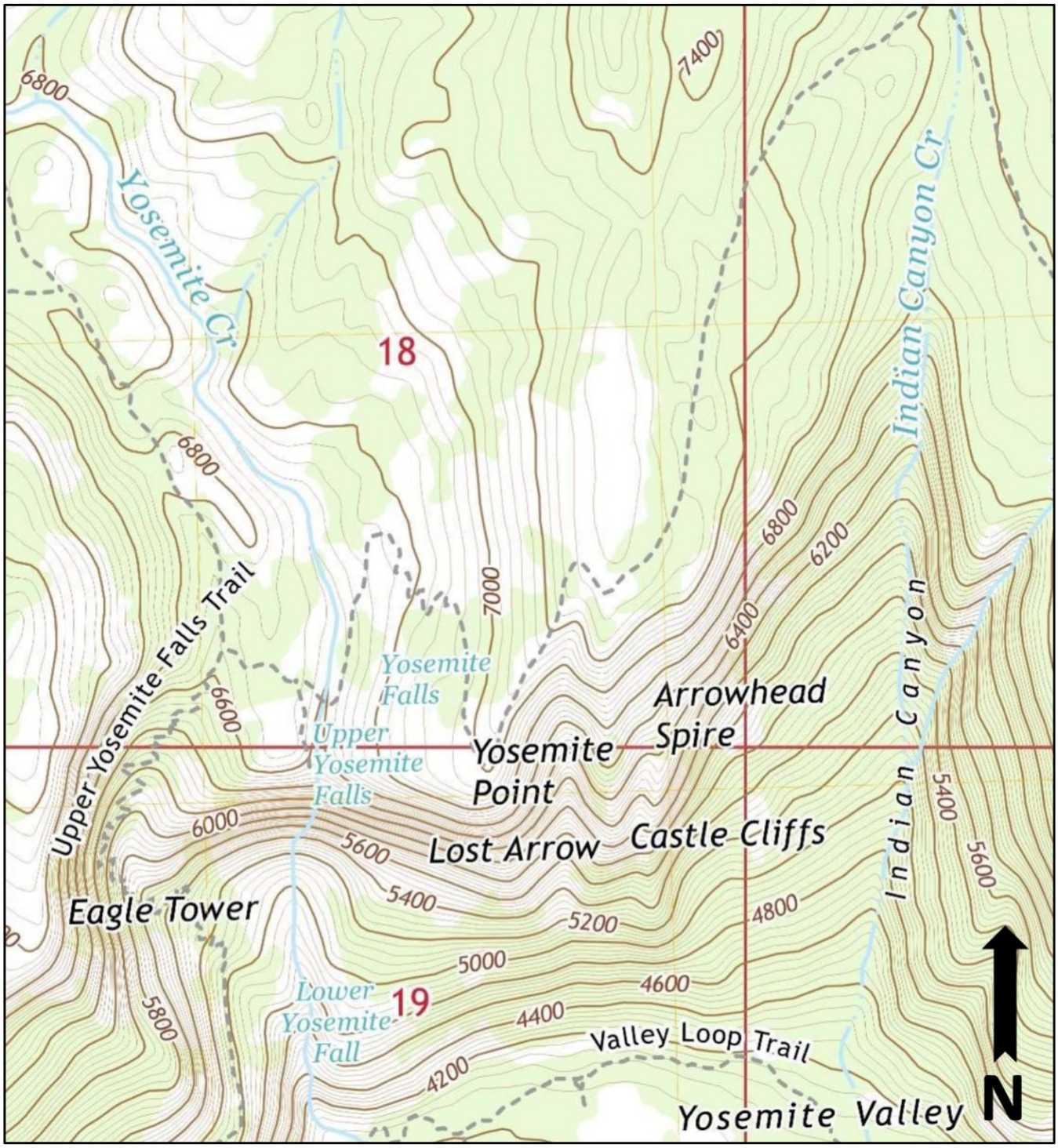


Figure 2.24: Topographic Map of Yosemite Falls, California.

1. Determine the contour interval of the map. *Show your work*.

2. Locate **Yosemite Creek**. In which direction does Yosemite Creek flow?

3. How were you able to determine the streamflow direction?

4. In general, where are the steepest areas on this map?
    a. North
    b. South

5. In general, where are the lower elevations on this map?
    a. North
    b. South

6. If you wanted to take an easy hike with your family, would you select the **Upper Yosemite Falls Trail** or the **Valley Loop Trail**? Why would you make this choice?

Attributions

- Figure 2.23: Derivative of “Yosemite Falls Quadrangle 7.5-Minute Series (2018)” (Public Domain, USGS) by Chloe Branciforte

Activity 2D: Latitude and Longitude

7. On **Figure 2.24** below, identify and label (at A-D) the following lines of latitude: **South Pole, North Pole, Tropic of Cancer, Tropic of Capricorn, Equator**

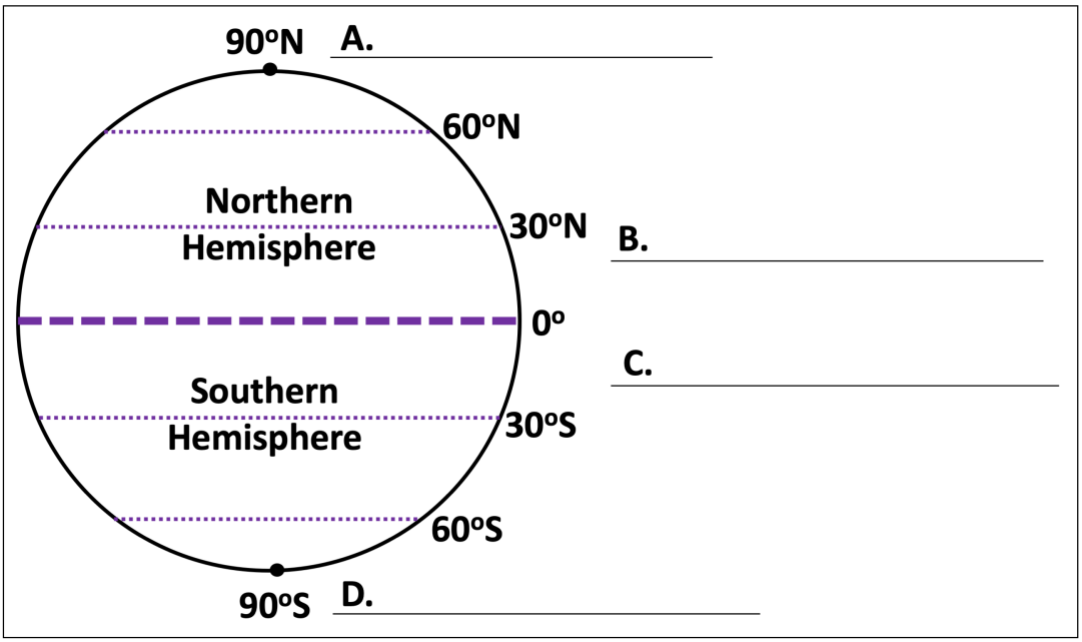


Figure 2.25: Label the lines of latitude indicated at A, B, C and D.

8. On **Figure 2.25** below, label the meridian highlighted at **A**.
   Is this a line of latitude or longitude?

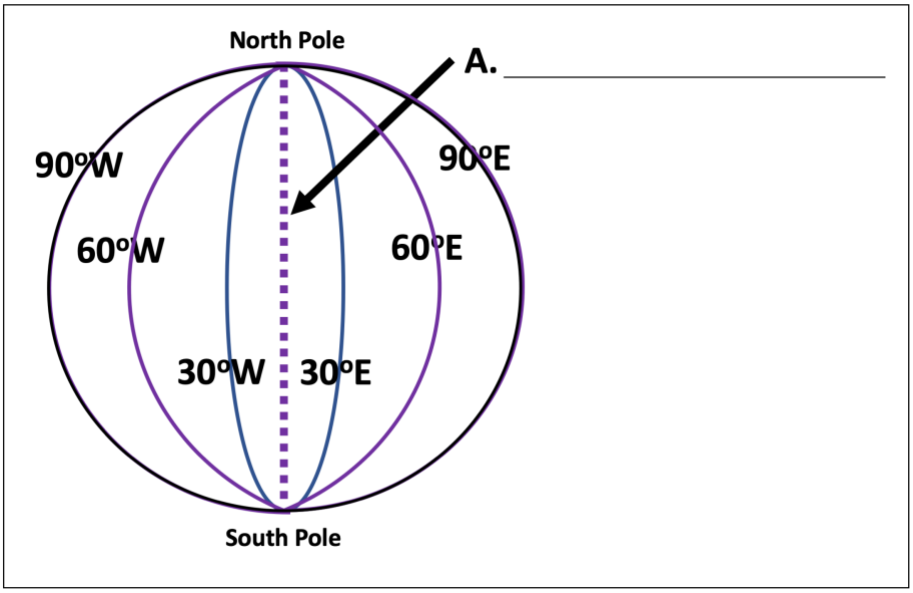


Figure 2.26: Label the major line of longitude indicated at A.

Attributions

- Figure 2.24: “Latitude Activity” (CC-BY 4.0; Chloe Branciforte and Cynthia Lampe, own work)
- Figure 2.25: “Longitude Activity” (CC-BY 4.0; Chloe Branciforte and Cynthia Lampe, own work)

Activity 2E: Latitude and Longitude on Topographic Maps

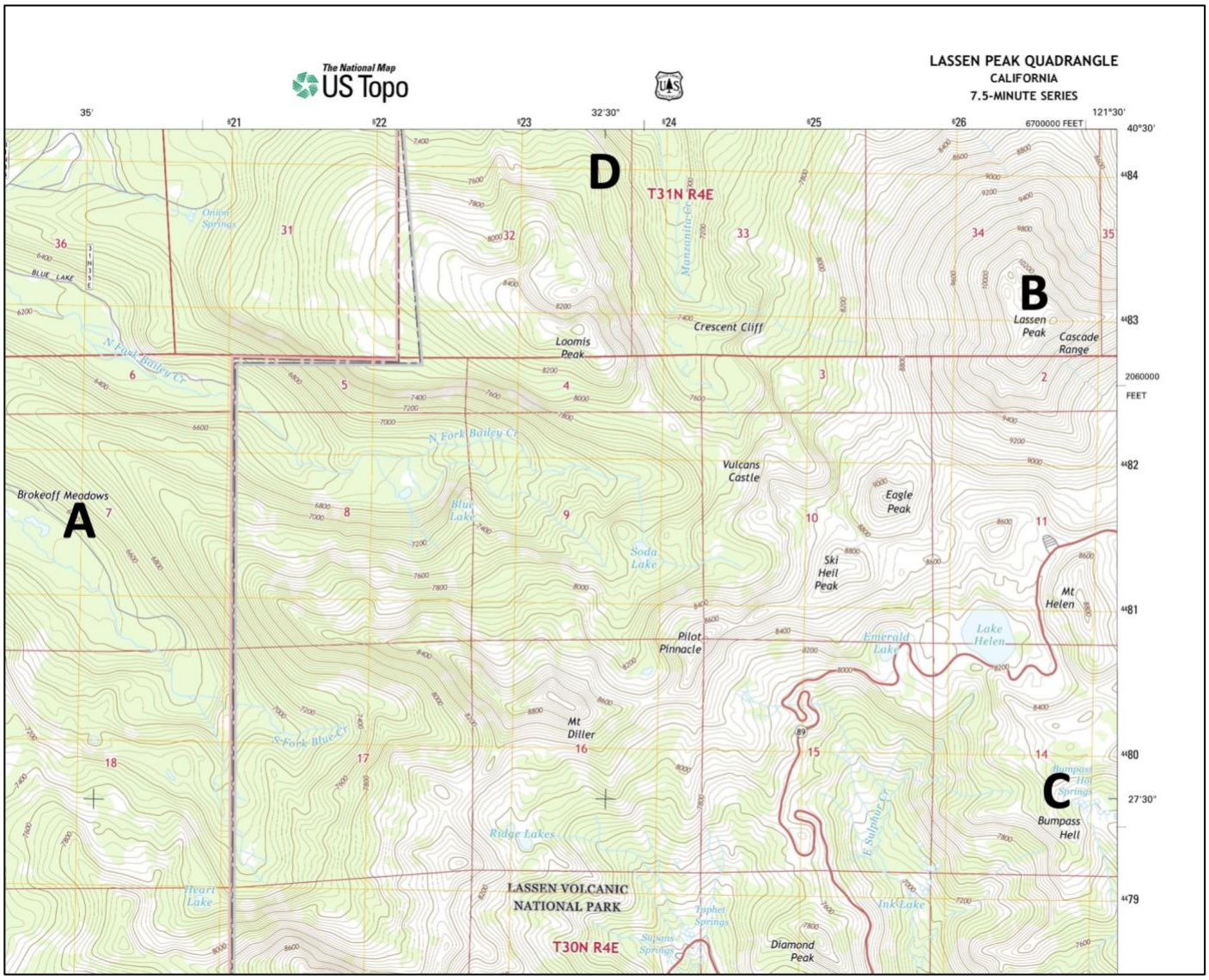


Figure 2.27: A topographic map of the Lassen Peak Quadrangle (2018).

1. Identify the latitude and longitude of **Point A (Brokeoff Meadows)** on the Lassen Peak Quadrangle (**Figure 2.26**). *Hint: be sure to write as, degrees, minutes, seconds.*

    a. Latitude:

    b. Longitude:

2. Identify the latitude and longitude of **Point B (Lassen Peak)** on the Lassen Peak Quadrangle. *Hint: be sure to write as, degrees, minutes, seconds.*

    a. Latitude:

    b. Longitude:

3. Identify the latitude and longitude of **Point C (Bumpass Hell)** on the Lassen Peak Quadrangle. *Hint: be sure to write as, degrees, minutes, seconds.*

    a. Latitude:

    b. Longitude:

4. Identify the latitude and longitude of **Point D** on the Lassen Peak Quadrangle. *Hint: be sure to write as, degrees, minutes, seconds.*

    a. Latitude:

    b. Longitude:

Attributions

- Figure 2.26: Derivative of “Lassen Peak Quadrangle” (Public Domain; USGS) by Chloe Branciforte

Activity 2F: Constructing a Topographic Profile

Construct a topographic profile for the contour map below (**Figure 2.27**). Recall, a topographic profile allows you to visualize the vertical component of a landscape. To successfully draw a topographic profile, remember to follow these simple steps,

To successfully draw a topographic profile, follow these simple steps or visit How do I construct a Topographic Profile? for additional help.

1. Locate a line on a map that is interesting. In many cases, this line is given to you (often labeled A-A' or A-B). Grab a piece of blank paper and place the edge along this line. Mark the starting and ending points of the line. Be sure you label them appropriately, as A and A', or A and B, or however the original line on the map is identified.
2. Start at one end, for example the A end, and move along the edge of the paper, making a mark on the paper every time a contour line touches the edge of the paper. Make sure you label each mark with the right elevation so that you can transfer that point to the correct elevation on your profile. It is important to write neatly to ensure they can be read during a later step. Note the highest and lowest elevation.
3. Use a piece of graph paper (or horizontally lined paper) that is at least as long as your profile line. If needed, tape paper together to a long enough sheet; make sure the grid lines line up.
4. On the graph paper, draw a horizontal line the length of the profile line. Draw vertical lines above your starting and ending points. Label the y-axis (vertical lines) with elevation. It is important to consider the scale, use the noted highest and lowest elevations from previous. For example, if the lowest elevation is 7,200 feet and the highest is 10,600 feet, you'd likely want to label your axis from 7,000 to 11,000 feet.
5. Line up your original tick marked paper with the line drawn on your graph paper. Beginning with the elevation on the left-hand side of the paper, go directly up from that tick mark to make a small dot at the corresponding elevation. Note that the point does not need to be on a vertical line on the graph paper.
6. Once you have transferred all of your tick marks to your graph paper, connect the dots using a smooth curve. When connecting dots, recall you are interpreting the land surface between contour lines and therefore want smooth and consistent lines, and not straight lines. If you compare your profile with a fellow classmate, you may notice slight differences; overall, however, they should be a similar shape.

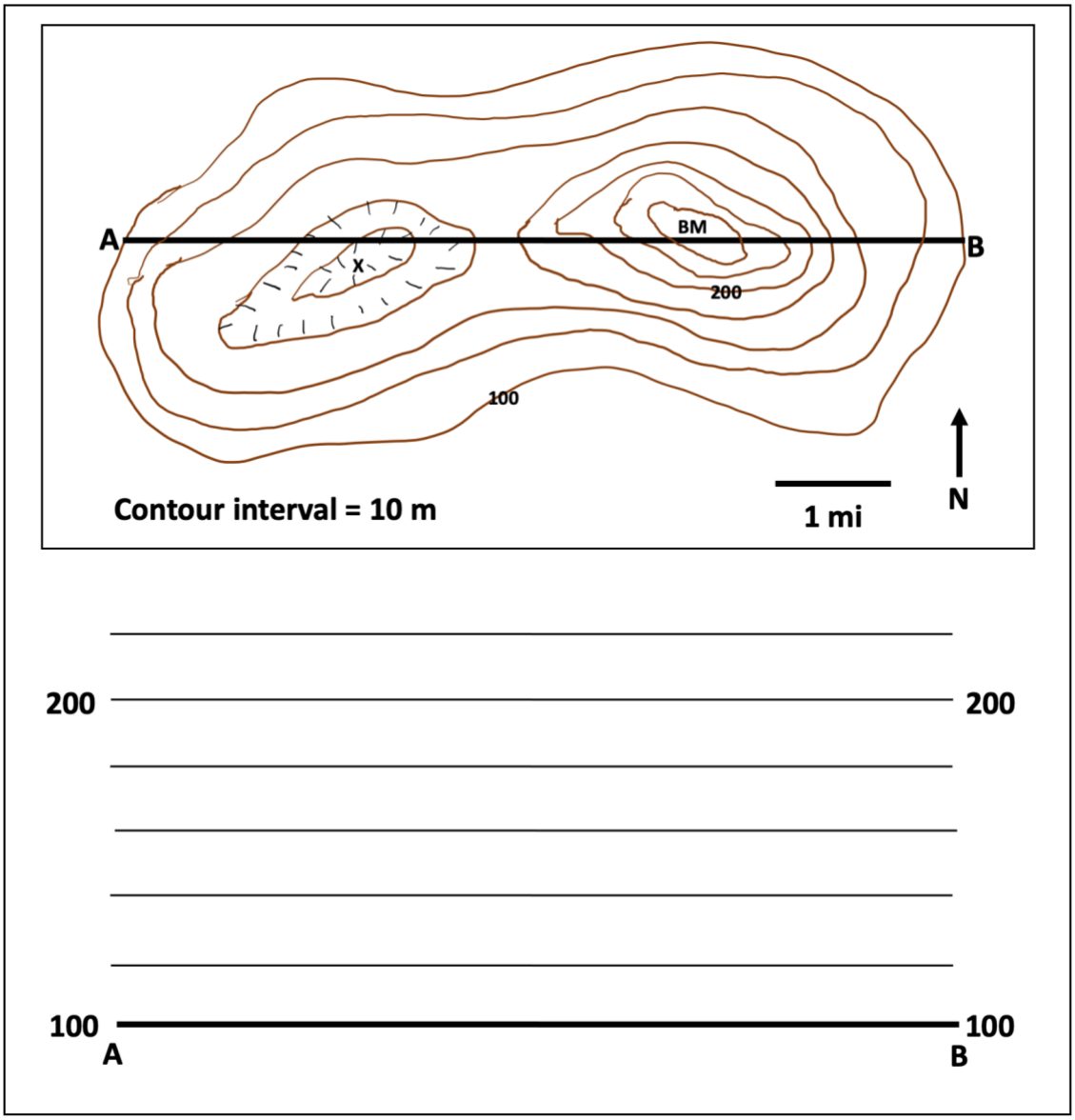


Figure 2.28: Topographic map and profile.

1. Using the Rule of Halves, **interpolate** (estimate an unknown value from neighboring known values) the elevation of:

    a. **Benchmark BM**:

    b. **Benchmark X**:

2. What is the **total relief** (highest elevation - lowest elevation) of this map?

Attributions

- Figure 2.27: “Topographic Profile” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 2G: How to Use Google Earth

In this laboratory manual we will primarily use the free **browser version of Google Earth**, and you may want to download free **Google Chrome**, to ensure it runs seamlessly.

To use the browser version of Google Earth, just **click this link** and it will open the program into a new browsing window. You are now free to search! Take the time to explore the program and learn how to switch between 2D and 3D views, use the measure feature (it looks like a comb along the left-hand toolbar), drop a place (pin), and become comfortable with how to move around the screen.

1. Search for your college. Zoom in and locate the science building.

2. Switch the view from 3D to 2D. Zoom in and out and then switch back to 3D.

3. Place a pin on the science building.

4. Measure the distance from the science building to the nearest parking lot in feet.

Loving Google Earth? You may be interested in **Google Earth Pro**. This program is also free but does require a program download to a computer as it is not compatible with most phones, tablets or chromebooks.

To download Google Earth Pro version 7.3:

- Go to https://www.google.com/earth/versions/
- Click on the Download Google Earth Pro icon at the top of the page.
- Click on the box which states, Download Google Earth Pro on Desktop.
- Review the Privacy Policy and click Accept & Download. This will download the latest version.
- Save the file to your desktop, open it and follow the instructions to install.
- Open Google Earth Pro.

Chapter 3: Minerals and Mineral Identification

Learning Outcomes

After completing this chapter, you should be able to:

- ✓ Determine the many different physical properties of minerals, and apply them to mineral identification.
- ✓ Distinguish mineral cleavage from mineral fracture.
- ✓ Identify the minerals assigned by your instructor.

Thumbnail image for chapter:

Thumbnail: "Benitoite, Neptunite, and Natrolite " (CC-BY 4.0; Chloe Branciforte, own work)

Have You Used a Mineral Today?

While many people may initially say no, consider these questions: Have you brushed your teeth? Have you eaten anything that contained salt? Did you put on make-up this morning? Have you painted your fingernails or toenails? Used a cellphone or other electronic device? Used a form of transportation, car, bike, or public transit? A yes to any of these questions, means you have used at least one mineral today, and likely probably many more! Minerals are useful and common in everyday products, yet most people do not even realize it (**Figure 3.1**).

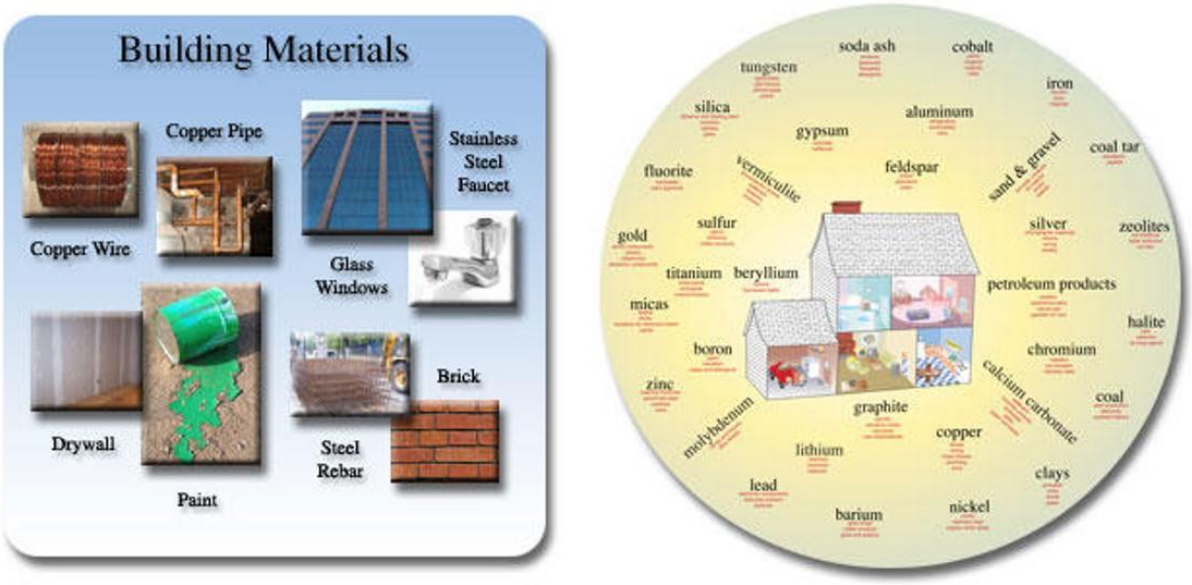


Figure 3.1: Common mined building materials, including minerals and other earth resources.

Minerals are not only important for their many uses, but also as the building blocks of rocks. In this lab, you will lay the foundation for many future labs in the course. Correct mineral identification is critical in geology, so work through this lab carefully. There are several thousand minerals, but we will focus on only the most common ones.

The geoscientists who study minerals are called mineralogists. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including in mining and natural resource extraction. Many of these career options require a college degree and postgraduate work (typically a PhD). If you are interested in mineralogy talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections,

including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 3.1: “Building Materials and Minerals” (Public Domain; USGS)

What Is a Mineral?

A **mineral** is defined as any *naturally occurring, inorganic solid with a definite chemical composition and a characteristic crystalline structure*. Let's break down this definition down.

- **Naturally occurring**, means that anything synthetic (human-made), does not count as a mineral.
- To be an **inorganic solid**, the mineral must not be composed of the complex carbon molecules that are characteristic of life and must be in the solid state, rather than vapor or liquid. This means that water, a liquid, is not a mineral, while water-ice, a solid, would be a mineral, provided it is out in nature and not synthetic.
- A **definite chemical composition** refers to a definable chemical formula. Some minerals will have short chemical formulas, like Halite (NaCl or sodium chloride). For other minerals, like Olivine ($(Mg,Fe)_2SiO_4$ or a magnesium iron silicate), the chemical formula becomes involved, as certain elements may substitute for another of similar size and charge.
- The atoms within minerals are lined up in an orderly fashion, so that the characteristic **crystalline structure** is just an outward manifestation of the internal atomic arrangement.

What Are the Physical Properties of Minerals?

Identifying a mineral is a bit like playing detective. Minerals are identified by their physical properties. **Physical properties** are assessed by using observational skills. Observe **Figure 3.2**: how would you describe the mineral in this image?

Figure 3.2: Sulfur from Baja California, Mexico.

You might describe this mineral as being yellow, with a shine and a distinct shape. Each description is actually a physical property (yellow = color, shiny = luster, shape = crystal form). As we learn more about minerals, it is important to note all available physical properties. Certain physical properties are referred to as **diagnostic**; this means they are useful in identifying a particular mineral by name. Those properties that are not diagnostic are still helpful, but often other properties are required for a proper identification. Color is a property that is frequently variable and should not be used as a diagnostic property. For example, quartz, an important rock-forming mineral, is available in a variety of colors; other properties would be necessary for an accurate identification. However, occasionally color can be helpful, as in the case of the mineral azurite. Azurite (from azure) is always blue in color.

Assessing the "importance" of one property over another, requires hours of practice with the minerals and their properties. This helps develop a mental mineral database, which can be used for future mineral identification. However, this database is only as good as the time and energy spent to develop it; *geology majors, take note*! Below are details regarding each of the physical properties to help identify minerals.

Attributions

- Figure 3.2: “Sulfur from Baja California, Mexico” (CC-BY 2.0; James St. John via Flickr)

Mineral Properties: Visual Properties

Properties can be organized into three major categories: visual, testable, and special or unique properties.

Color

This represents the outward color of the mineral and reflects atomic bonding or trace impurities. The outward color may be light, dark or anywhere in between. The color could be solid or mottled, and may even show **iridescence** (**Figure 3.3**).

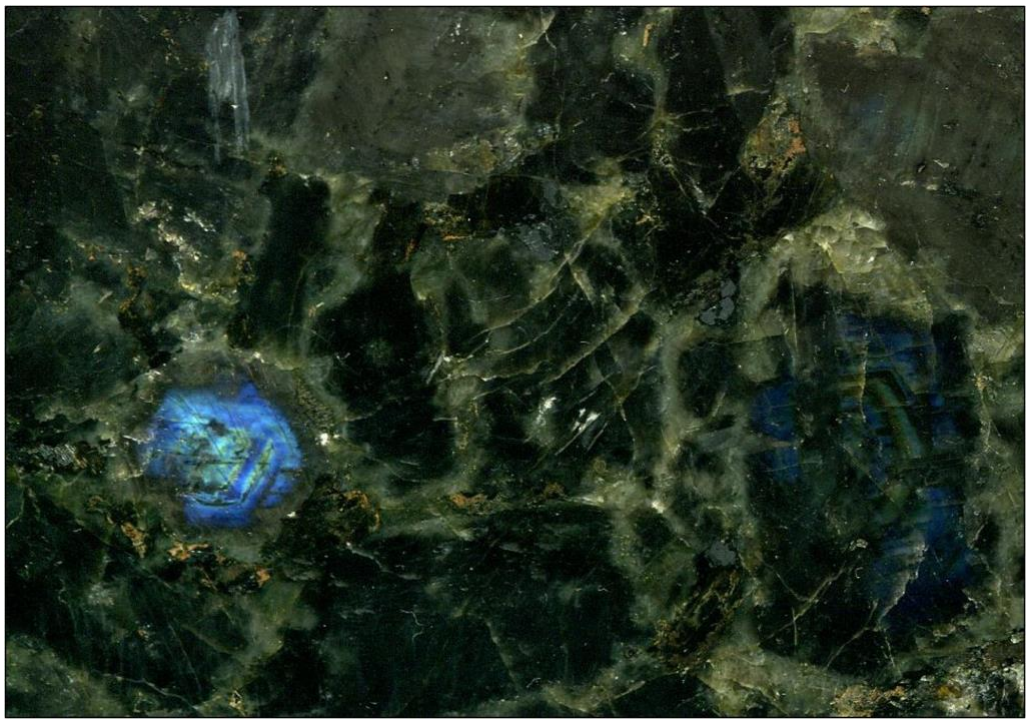


Figure 3.3: The mineral labradorite, which displays iridescence.

Clarity

This represents the minerals' ability to transmit light. If light is easily passed through, and the mineral is see-through, it is described as being transparent. If light cannot pass through a mineral it is described as being opaque. If a mineral can pass light through, but is unable to be see-through, it is described as translucent. Certain minerals may have unique optical properties, like double refraction or fiber optics.

Luster

Luster refers to the appearance of the reflection of light from a mineral's surface. Typically, there are two major luster categories, metallic, and non-metallic**.** Minerals with a **metallic luster** are typically opaque and appear as tarnished metal to a polished metal surface (**Figure 3.4, left**). A **non-metallic luster** encapsulates many possible appearances, from earthy to pearly, waxy to dull, glassy to silky (**Figure 3.4, right**). Submetallic lusters are also possible, and more subtle than a true metallic luster.

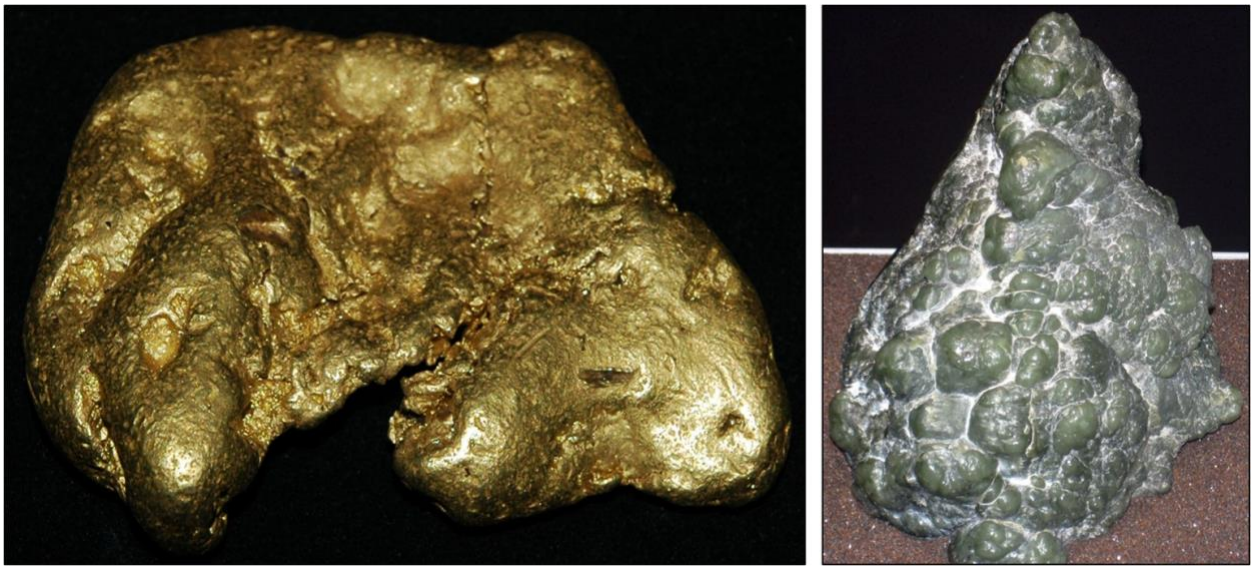


Figure 3.4: *Left:* A gold nugget from California displaying a metallic luster. *Right:* Botryoidal nephrite jade from California displaying a non-metallic, waxy luster.

Crystal Shape, Form or Habit

By definition all minerals are crystals, however some minerals will have a distinct **crystal shape** (**Figure 3.5**). This shape is determined by the minerals' growth space. If a mineral has time and space to develop it forms crystals faces. These faces intersect to form a distinct crystal shape. Perfect crystals are rare, and are often what we associate with minerals viewed in a museum. Should a mineral not have space to grow, then no distinct crystal shape will develop. A mineral with no distinct geometry is given the term **massive or compact**.

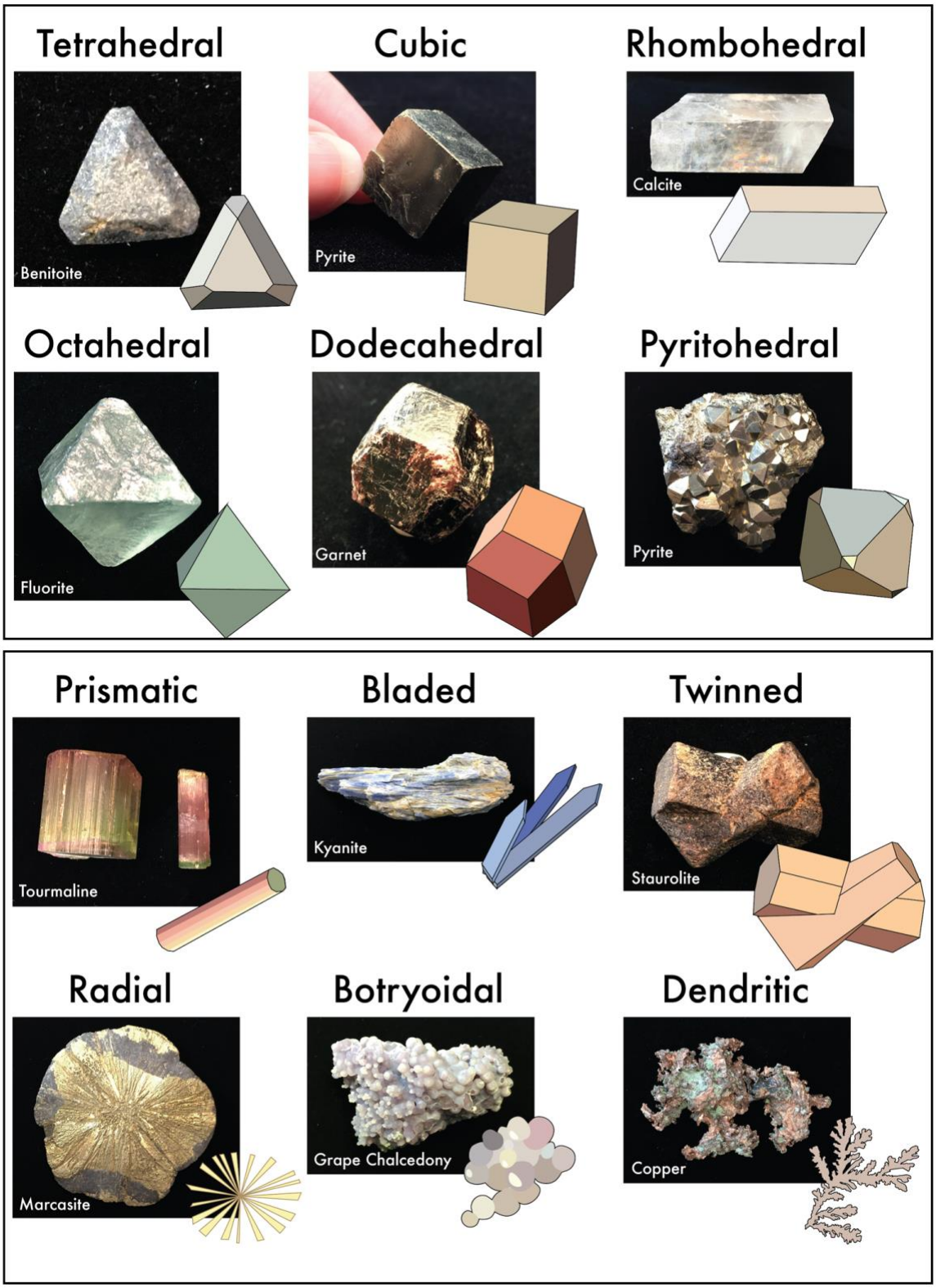


Figure 3.5: Various crystal habits and representative mineral examples.

Attributions

- Figure 3.3: “Volga Blue Granite” (CC-BY 2.0; James St. John via Flickr)
- Figure 3.4: Derivative of “Gold Nugget” (CC-BY 2.0; James St. John via Flickr) and “Botryoidal Nephrite Jade” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte
- Figure 3.5: “Crystal Habits” (CC-BY 4.0; Emily Haddad, own work)

Mineral Properties: Testable Properties

Heft & Specific Gravity

Heft is related to **specific gravity**, or density, of the mineral. When geologists are in the field they are unable to take with them the equipment necessary to calculate specific gravity. Instead the heft test is preferred. The mineral is held in the palm of the hand, and the overall heaviness of the mineral is assessed. Does the mineral feel very heavy for its size? Very light? The chemistry of certain minerals, for example the metal bearing minerals, will often result in a high heft and feel heavy in your palm. Other minerals, like kaolinite or sulfur will feel relatively lighter in heft for their size.

Specific gravity is the ratio of a mineral's weight to the weight of an equal volume of water. A mineral with a specific gravity of 2 would weigh twice as much as water. Most minerals are heavier than water, and the average specific gravity for all minerals is approximately 2.7. Some minerals are quite heavy, such as pyrite with a specific gravity of 4.9-5.2, native copper, with a specific gravity of 8.8-9.0, and native gold at 19.3, which makes panning useful for gold, as the heavy mineral stays behind as you wash material out of the pan.

Feel

This is how the mineral feels beneath your fingertips. We want to move away from the term "texture", as this term will have a distinct meaning as we move into our rock units. Minerals may have a distinct feel: for example, olivine typically has a gritty or granular feel, whereas talc often feels greasy or soapy.

Figure 3.6: Streak plate with Pyrite (left) and Rhodochrosite (right) and their characteristic streak color.

Streak

Streak is the color of the mineral left behind on an unglazed porcelain plate, or a streak plate (**Figure 3.6**). A mineral's streak color may be different from its outward color. Many minerals have a white streak, which is not particularly diagnostic. However, a mineral with a colored streak – black, blue, gray, green, or red – is often diagnostic. If you are ever unsure of the streak color, wipe your finger along the streak plate; a mineral with a white streak will leave a white powder behind that will rub on your finger. If your instructor provides both a white and black streak plate, try streaking the mineral on both plates. Recall, if

a mineral is harder than the ceramic streak plate, you will see a porcelain powder from the plate and not from the mineral.

Tenacity

Tenacity refers to the way a mineral resists breakage and represents the brittleness, flexibility or malleability of a mineral. It is different from a mineral's hardness. If a mineral shatters like glass, it is said to be **brittle**, like quartz, while minerals that can be hammered are **malleable**, like copper or gold. Minerals may be **elastic**, in which they are flexible and bend like a plastic comb but return to their original shape, like the micas. **Sectile** minerals are soft like wax, and can be separated with a knife, like gypsum.

Hardness

Hardness refers to the resistance of a mineral to being scratched by a different mineral or other material and is a product of the strength of the bonds between the atoms of a mineral. Whatever substance does the scratching is harder; the item scratched is softer. Hardness is based on a scale of 1 to 10, the **Mohs Hardness Scale**, created by a mineralogist named Friedrich Mohs (**Table 3.1**).

Mohs Hardness Scale		
Hardness number	**Mineral**	**Test kit item**
10 (hardest)	Diamond	
9	Corundum	
8	Topaz	*8.5 - Masonry drill bit*
7	Quartz	
6	Feldspar	*6.5 - Steel nail*
5	Apatite	*5.5 - Glass plate or knife blade*
4	Fluorite	
3	Calcite	*3.5 - Copper*
2	Gypsum	*2.5 - fingernail*
1 (softest)	Talc	

Table 3.1: Mohs Hardness Scale is a relative hardness scale, where 1 represents a soft mineral, like talc, and 10 represents a hard mineral, like diamond.

The Mohs' scale lists ten minerals in order of relative hardness. Each mineral on the scale can scratch a mineral of a lower number. Your mineral kits will likely contain several items of a known hardness. The glass plate and steel nail have a hardness of 5.5, a copper penny, plate or sheet has a hardness of 3, and your fingernail has a hardness of 2.5. A mineral scratched by your fingernail is relatively soft, and its assessed hardness would be <2.5. When trying to scratch a surface, use force, but be cautious with the glass plate. ***ALWAYS lay the glass plate on a flat surface rather than holding it in your hand***.

Occasionally mineral powder is left behind when a soft mineral scratches a harder surface, so feel for the groove or scratch. Materials of similar hardness may have difficulty scratching each other. For example, hornblende (amphibole) typically has a hardness right around glass, so it may or may not leave a scratch on the glass surface.

Breakage

Minerals, even those with high hardness, can break. Typically, minerals break in one of two ways. A mineral can break with **fracture** or with **cleavage**. The type of breakage is dependent on the chemical bonds that are present at the atomic level of the mineral. There are many types of chemical bonds and forces that bind molecules together. The two most basic types of bonds are characterized as either ionic or covalent. In **ionic bonding**, electrons are being transferred from one atom to another in an ionic bond (**Figure 3.7, left**). These bonds are important to the formation of many minerals and are very strong. In contrast, **covalent bonds** share electrons and are also often strong bonds (**Figure 3.7, right**). Most minerals are characterized by ionic bonds, covalent bonds, or a combination of the two, but there are other types of bonds that are important in minerals, including **metallic bonds** and weaker electrostatic forces (**hydrogen** or **Van der Waals bonds**). Metallic elements have outer electrons that are relatively loosely held. When bonds between such atoms are formed, these electrons can move freely from one atom to another. A metal can thus be thought of as an array of positively charged atomic nuclei immersed in a sea of mobile electrons. This feature accounts for two very important properties of metals: their electrical conductivity and their malleability. Molecules that are bonded ionically or covalently can also have other weaker electrostatic forces holding them together. Examples of this are the force holding graphite sheets together and the attraction between water molecules.

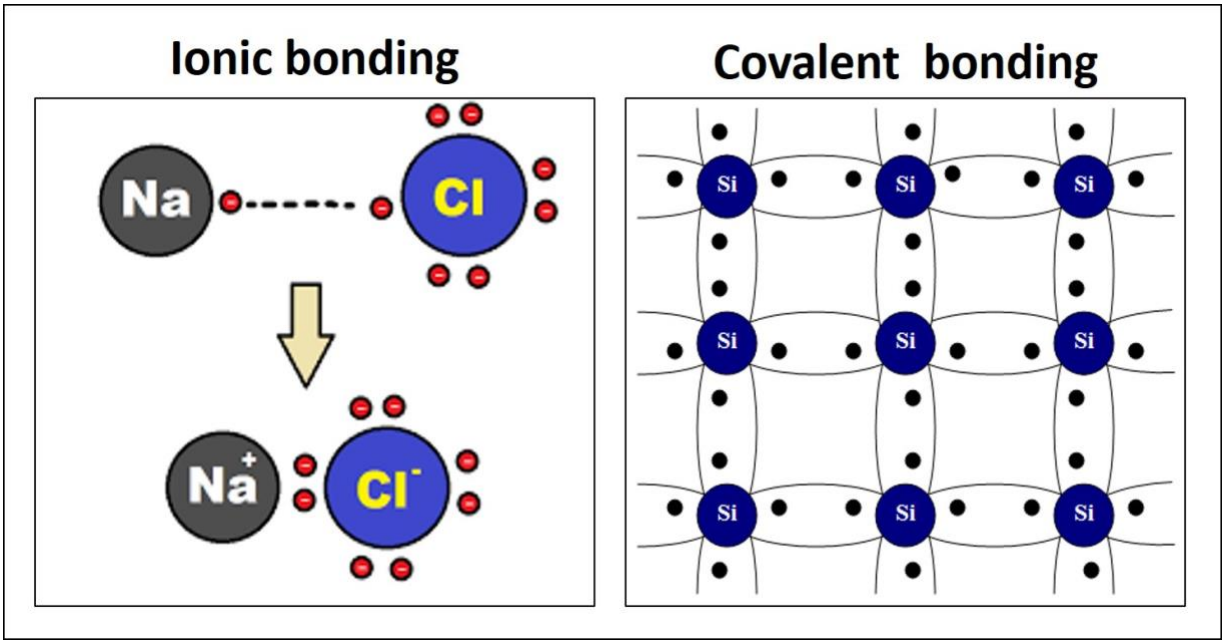


Figure 3.7: An example of ionic bonding in sodium chloride (NaCl) *(left)*; an example of silicon covalent bonding *(right)*.

Recall, all minerals are characterized by a specific three-dimensional pattern known as a lattice or crystal structure. These structures range from the simple cubic pattern of halite (NaCl), to the very complex patterns of some silicate minerals. Two minerals may have the same composition, but very different crystal structures and properties are known as **polymorphs**. Graphite and diamond, for example, are both composed only of carbon, but while diamond is the hardest substance known, graphite is softer than paper. **Mineral lattices** have important implications for mineral properties. Lattices also determine the shape that mineral crystals grow in and how they break. For example, the right angles in the lattice of the mineral halite influence both the shape of its crystals (typically cubic), and the way those crystals break.

Fracture

A mineral which contains chemical bonds that are equal, and the same throughout, will not have a pattern of breakage and is said to exhibit **fracture**. This results in breakage that looks like when you break a glass or plate at home. Fracture surfaces are commonly uneven or **conchoidal**, a ribbed, smoothly curved surface similar to broken glass.

Cleavage

A mineral which contains chemical bonds that are unequal, and are different throughout, will result in a pattern of breakage called **cleavage**. This results in breakage with a shape that looks like itself, every time the mineral is broken. As minerals are broken (such as with a rock hammer), any cleavage planes will result in flat surfaces parallel to the directions of weakness within the crystal, these are the zones of weakness.

A mineral may have one or more cleavage planes (**Figure 3.8**). Planes that are parallel are considered the same direction of cleavage and should only count as one.

- **One direction of cleavage** is termed basal or sheet cleavage. Minerals that display this cleavage will break off in flat sheets.
- **Two directions of cleavage** is termed prismatic.
- **Three directions of cleavage at 90°** is termed cubic.
- **Three directions of cleavage NOT at 90°** is termed rhombic.
- **Four directions of cleavage** is termed octahedral.

When 2 or more cleavage planes are present, it is important to pay attention to the angle of the cleavage planes. To determine the angle of cleavage, look at the intersection of cleavage planes. Commonly, cleavage planes will intersect at 90° (right angles) or 60°/120°. It can be challenging to distinguish cleavage from crystal form, particularly in imperfect samples. However, crystal form occurs as a mineral grows, while cleavage develops as a mineral breaks.

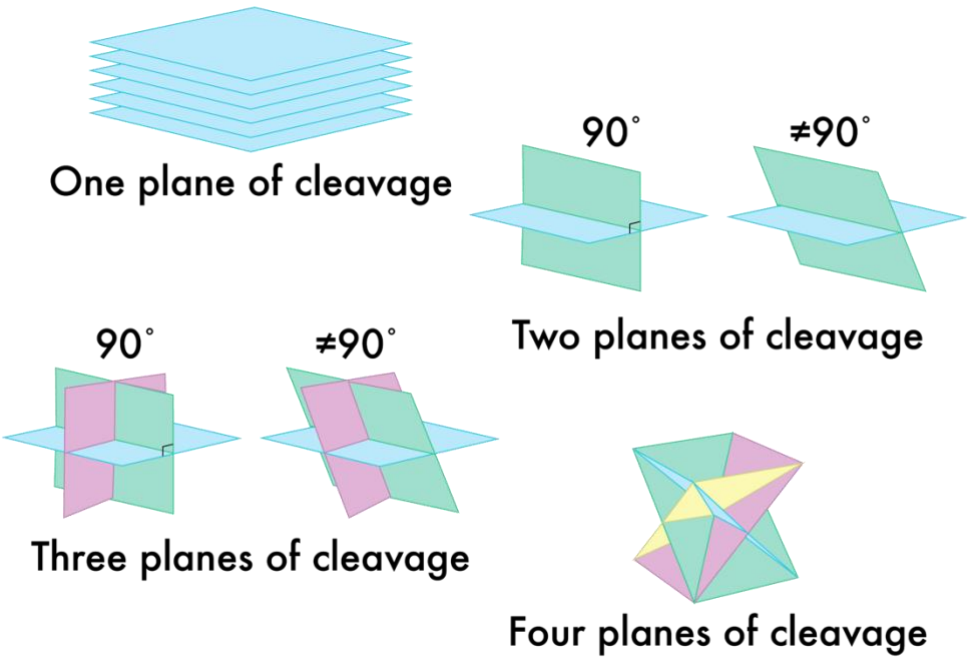


Figure 3.8: Various cleavage planes and directions.

Attributions

- Figure 3.6: “Streak Plate with Pyrite and Rhodochrosite” (CC-BY-SA 3.0; Ra’ike via Wikipedia)
- Table 3.1: “Mohs Hardness Scale” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 3.7: Derivative of “Ionic Bonding” (CC-BY-SA 3.0; Rhannosh via Wikimedia Commons) and “Silicon Covalent Bond” (Public Domain; Hermitage17 via Wikimedia Commons) by Chloe Branciforte
- Figure 3.8: “Mineral Cleavage Planes” (CC-BY 4.0; Emily Haddad, own work)

Special or Unique Properties

Effervescence

Some minerals react when dilute hydrochloric acid (HCl) is placed on them (**Figure 3.9**). When hydrochloric acid is introduced to a mineral, like **calcite**, a carbonate mineral, a chemical reaction occurs. The mineral effervesces, fizzes or bubbles and releases carbon dioxide gas. When you test a mineral with acid, be cautious and use just a drop of the acid. Use your magnifying glass to look closely for bubbles. The acid is very dilute and will not burn your skin or clothing, but you should always wash your hands after use. Also make sure that you rinse with water and wipe off the acid from the minerals that you test. Occasionally, vinegar can also be used, but larger quantities are necessary and the reaction becomes muted.

Figure 3.9: Calcite reacting (bubbling) with the addition of dilute (1M) hydrochloric acid (HCl).

Magnetism

Certain metal bearing minerals will be attracted to a magnet. **Magnetite**, an iron oxide, is an important mineral in sea floor striping; stripes oriented parallel to mid-ocean ridges, which will be discussed more in Plate Tectonics.

Taste

Some minerals have distinct tastes, which can be useful in determining the mineral name. Commonly, the **halides** can be tasted and, in the case of **halite**, taste familiar (it is common table salt!). Other salts will have more bitter or sweet flavors depending on the types. However, ***YOU SHOULD NEVER TASTE UNKNOWN MINERALS***. Tasting unknown minerals is an unsafe practice, as there are many minerals that you should not ingest. Only taste minerals cleared by your instructor.

Smell

Commonly, **sulfur** bearing minerals have a distinct rotten egg odor. This can be a clue to the

chemical composition of the mineral, which points to specific mineral groups and eliminates others. When smelling minerals ***do not smell the mineral directly***, instead **waft** the smell to your nose.

Fluorescence

Fluorescent minerals are those that emit visible light when activated by invisible ultraviolet light (UV), X-rays and/or electron beams. Certain electrons in the mineral absorb the energy from these sources and jump to a higher energy state, this results in many of the dayglo colors (**Figure 3.10**).

Figure 3.10: Fluorescent mineral display at the Santa Barbara Natural History Museum. Image on the right displays the minerals under ultraviolet light.

Attributions

- Figure 3.9: “Effervescence” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 3.10: “Fluorescent Minerals” (CC-BY 4.0; Chloe Branciforte, own work)

Mineral Groups

Most minerals are made up of a **cation** (a positively charged ion) or several cations and an **anion** (a negatively charged ion). For example, in the mineral hematite (Fe_2O_3), the cation is Fe^{3+} (iron) and the anion is O^{2-} (oxygen). We group minerals into classes on the basis of their predominant anion or **anion group**. Groups include the oxides, sulfides, carbonates, silicates, and others. The **silicates** are by far the predominant group in terms of their abundance within the crust and mantle. Examples of common minerals from the different groups are given in **Table 3.2**.

Mineral Group	Mineral Examples
Oxides	Hematite, corundum, water ice
Sulfides	Galena, pyrite, chalcopyrite
Sulfates	Gypsum, barite,
Halides	Fluorite, halite
Carbonates	Calcite, dolomite
Phosphates	Apatite, Turquoise
Silicates	Quartz, feldspar, olivine
Native minerals	Gold, diamond, graphite, sulfur, copper

Table 3.2: Significant mineral groups and associated mineral examples.

What Do These Mineral Groups Mean?

Oxide minerals have oxygen (O^{2-}) as their anion, but they exclude those with oxygen complexes such as carbonate (CO_3^{2-}), sulfate (SO_4^{2-}), and silicate (SiO_4^{4-}). The most important oxides are the iron oxides hematite and magnetite (Fe_2O_3 and Fe_3O_4, respectively). Both of these are important ores of iron. Corundum (Al_2O_3) is an abrasive, but can also be a gemstone in its ruby and sapphire varieties. If the oxygen is also combined with hydrogen to form the hydroxyl anion (OH^-) the mineral is known as an hydroxide. Some important hydroxides are limonite and bauxite, which are ores of iron and aluminum respectively. Frozen water (H_2O) is a mineral (an oxide), but liquid water is not because it doesn't have a regular lattice.

Sulfides are minerals with the S^{2-} anion, and they include galena (PbS), sphalerite (ZnS), chalcopyrite ($CuFeS_2$), and molybdenite (MoS_2), which are the most important ores of lead, zinc, copper, and molybdenum, respectively. Some other sulfide minerals are pyrite (FeS_2), bornite (Cu_5FeS_4), stibnite (Sb_2S_3), and arsenopyrite (FeAsS).

Sulfates are minerals with the SO_4^{2-} anion, and these include anhydrite ($CaSO_4$) and its cousin gypsum ($CaSO_4 \cdot 2H_2O$) and the sulfates of barium and strontium: barite ($BaSO_4$) and celestite ($SrSO_4$). In all of these minerals, the cation has a +2 charge, which balances the –2 charge on the sulfate ion.

The **halides** are so named because the anions include the halogen elements chlorine, fluorine, bromine, etc. Examples are halite (NaCl), cryolite (Na_3AlF_6), and fluorite (CaF_2).

The **carbonates** include minerals in which the anion is the CO_3^{2-} complex. The carbonate combines with +2 cations to form minerals such as calcite ($CaCO_3$), magnesite ($MgCO_3$), dolomite ($(Ca,Mg)CO_3$), and siderite ($FeCO_3$). The copper minerals malachite and azurite are also carbonates.

In **phosphate** minerals, the anion is the PO_4^{3-} complex. An important phosphate mineral is apatite ($Ca_5(PO_4)_3(OH)$), which is what your teeth are made of.

The all-important **silicate** minerals include the elements silicon and oxygen in varying proportions ranging from $Si:O_2$ to $Si:O_4$.

Native element minerals are single-element minerals, such as gold, copper, sulfur, and graphite.

Attributions

- Table 3.2: “Mineral Groups” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 3A: Assessing Hardness Values of Minerals

Materials Needed

- Mineral kit, provided by your instructor. This will likely contain numbered samples.
- Hardness kit:
    - Your fingernail
    - A copper penny, plate or wire
    - Glass plate or knife blade
    - Steel nail
- Streak plate (unglazed porcelain), preferably one white and one black plate.
- Hydrochloric acid (HCl), 1M is best. Gloves and protective goggles may be required for acid use; talk with your instructor.
- Hand lens or magnifying glass (at minimum 10x). ***How do I use a hand lens?*** *Hold it very close to your eye and bring the sample near the lens until it is in focus.*
- Optional: magnet, UV light, or other special equipment.

Recall, *hardness is the scratching resistance of a mineral*. You will need to determine if the mineral is harder or softer than the common material (**Table 3.1**). Use greater than (>) or less than (<) symbols to indicate the approximate hardness. For example, if your fingernail scratches your sample, look and feel for a gouge or groove in the sample, this sample would represent a hardness value of less than 2.5 (H<2.5).

Mohs Hardness Scale		
Hardness number	**Mineral**	**Test kit item**
10 (hardest)	Diamond	
9	Corundum	
8	Topaz	*8.5 - Masonry drill bit*
7	Quartz	
6	Feldspar	*6.5 - Steel nail*
5	Apatite	*5.5 - Glass plate or knife blade*
4	Fluorite	
3	Calcite	*3.5 - Copper*
2	Gypsum	*2.5 - fingernail*
1 (softest)	Talc	

Table 3.1: Mohs Hardness Scale is a relative hardness scale, where 1 represents a soft mineral, like talc, and 10 represents a hard mineral, like diamond.

Your instructor will indicate which three minerals to assess for this section. Use Table 3.1 for guidance.

1. Sample number:
    - **a.** Does your fingernail scratch this sample? *YES* *NO*
    - **b.** Does your sample scratch the copper or penny? *YES* *NO*
    - **c.** Does your sample scratch the glass? *YES* *NO*

2. Sample number:
    - **a.** Does your fingernail scratch this sample? *YES* *NO*
    - **b.** Does your sample scratch the copper or penny? *YES* *NO*
    - **c.** Does your sample scratch the glass? *YES* *NO*

3. Sample number:
    - **a.** Does your fingernail scratch this sample? *YES* *NO*
    - **b.** Does your sample scratch the copper or penny? *YES* *NO*
    - **c.** Does your sample scratch the glass? *YES* *NO*

Attributions

- Table 3.1: “Mohs Hardness Scale” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 3B: Assessing Crystal Shape/Form

Your instructor will indicate which minerals to assess for this section. Use Figure 3.5 for guidance.

1. Sample number: Crystal shape:

2. Sample number: Crystal shape:

3. Sample number: Crystal shape:

4. Sample number: Crystal shape:

5. Sample number: Crystal shape:

Activity 3C: Assessing Breakage

Your instructor will indicate which minerals to assess for this section. Use Figure 3.8 for guidance.

Sample number:

Does this mineral show cleavage or fracture?

If the sample shows cleavage, answer the following questions by circling the correct answer,

How many planes of cleavage is visible? **1** **2** **3** **4**

If more than one, are cleavage directions: **at 90°** **not at 90°** **?**

Which three-dimensional shape is created by this type of cleavage?

Cubic **Rhombohedral** **Sheet/Basal** **Octahedral**

Sample number:

Does this mineral show cleavage or fracture?

If the sample shows cleavage, answer the following questions by circling the correct answer,

How many planes of cleavage is visible? **1** **2** **3** **4**

If more than one, are cleavage directions: **at 90°** **not at 90°** **?**

Which three-dimensional shape is created by this type of cleavage?

Cubic **Rhombohedral** **Sheet/Basal** **Octahedral**

Sample number:

Does this mineral show cleavage or fracture?

If the sample shows cleavage, answer the following questions by circling the correct answer,

How many planes of cleavage is visible? **1** **2** **3** **4**

If more than one, are cleavage directions: **at 90°** **not at 90°** **?**

Which three-dimensional shape is created by this type of cleavage?

Cubic **Rhombohedral** **Sheet/Basal** **Octahedral**

Sample number:

Does this mineral show cleavage or fracture?

If the sample shows cleavage, answer the following questions by circling the correct answer,

How many planes of cleavage is visible? **1** **2** **3** **4**

If more than one, are cleavage directions: **at 90°** **not at 90°** **?**

Which three-dimensional shape is created by this type of cleavage?

Cubic **Rhombohedral** **Sheet/Basal** **Octahedral**

Sample number:

Does this mineral show cleavage or fracture?

If the sample shows cleavage, answer the following questions by circling the correct answer,

How many planes of cleavage is visible? **1** **2** **3** **4**

If more than one, are cleavage directions: **at 90°** **not at 90°** **?**

Which three-dimensional shape is created by this type of cleavage?

Cubic **Rhombohedral** **Sheet/Basal** **Octahedral**

Sample number:

Does this mineral show cleavage or fracture?

If the sample shows cleavage, answer the following questions by circling the correct answer,

How many planes of cleavage is visible? **1** **2** **3** **4**

If more than one, are cleavage directions: **at 90°** **not at 90°** **?**

Which three-dimensional shape is created by this type of cleavage?

Cubic **Rhombohedral** **Sheet/Basal** **Octahedral**

Sample number:

Does this mineral show cleavage or fracture?

If the sample shows cleavage, answer the following questions by circling the correct answer,

How many planes of cleavage is visible? **1** **2** **3** **4**

If more than one, are cleavage directions: **at 90°** **not at 90°** **?**

Which three-dimensional shape is created by this type of cleavage?

Cubic **Rhombohedral** **Sheet/Basal** **Octahedral**

Sample number:

Does this mineral show cleavage or fracture?

If the sample shows cleavage, answer the following questions by circling the correct answer,

How many planes of cleavage is visible? **1** **2** **3** **4**

If more than one, are cleavage directions: **at 90°** **not at 90°** **?**

Which three-dimensional shape is created by this type of cleavage?

Cubic **Rhombohedral** **Sheet/Basal** **Octahedral**

Activity 3D: Mineral Identification Chart

***Procedure*: How to Fill Out the Chart Below**

- **Sample number:** Write the sample number for the mineral in this column.
- **Color & Clarity:** What is the outward color of the mineral? What is the clarity of the mineral?
- **Luster:** Does the sample exhibit metallic or non-metallic luster? If it has a non-metallic luster can a more descriptive term be applied, for example, glassy, waxy, pearly, etc.
- **Crystal form:** If present, describe the crystal form. Rhombohedron, dodecahedron, hexagonal, etc.
- **Streak:** What color is the streak?
- **Hardness:** What is the approximate hardness? Using less than (<) or greater than (>) symbols with the common tools on the Mohs scale can be helpful here.
- **Breakage:** What breakage does the sample exhibit? Does it have fracture or cleavage? If the sample has cleavage, describe the number of planes and the degree of intersection.
- **Other properties:** Does the sample have any other or unique properties? Consider heft, feel, tenacity, effervescence, magnetism, taste, smell, fluorescence.

Once all properties have been gathered they can be used to identify the mineral by name.

Sample #	Visual properties			Testable properties				Mineral Name
	Color & Clarity	Luster	Crystal form	Streak color	Hardness	Breakage	Other properties (heft, feel, tenacity, effervescence, magnetism, taste, smell, fluorescence, other)	

Mineral Appendix:
Common Minerals and Their Properties

Amphibole: Hardness value right around glass (~5.5-6); green to black, elongate, or rod-shaped crystals common; two cleavage directions not at 90°.

Augite: Hardness value right around glass (~5.5-6); blocky green to black crystals common; two cleavage directions at 90°.

Biotite: Dark colored mica mineral; sheet cleavage (1 direction); flexible.

Calcite: Reacts with HCl; rhombohedral shape and cleavage.

Corundum: hexagonal shape with flat ends; hardness of 9; many colors common, lab kits generally have dull, brown or purple varieties. If gem quality, red = ruby; blue = sapphire.

Dolomite: Reacts with HCl only when powdered; rhombohedral shape and cleavage.

Fluorite: Commonly cleaves in octahedral shapes. Hardness is less than glass, but greater than copper. Many colors are common.

Galena: High heft; cube-shaped crystals common; silvery-blue color.

Garnet: Typically dark red in color (although there are many varieties); may have **hackly** or uneven fracture; dodecahedron shape common.

Graphite: Soft, greasy feel; will leave marks on paper.

Gypsum: Soft, may be tabular or fibrous; transparent to opaque.

Halite: Cubic crystals common; waxy feel; taste is distinct.

Hematite: Brick-red streak; may be earthy or metallic in luster.

Hornblende: Hardness value right around glass (~5.5-6); green to black, elongate, or rod-shaped crystals common; two cleavage directions not at 90°.

Kaolinite: Soft, earthy, white; massive; sticks to tongue.

Kyanite: Blue color; bladed crystals; two different hardness values, H = 5, parallel to blade; H = 7 across blade.

Magnetite: Magnetic; metallic; harder than glass.

Muscovite: Colorless mica; sheet cleavage; transparent, flexible sheets.

Olivine: Green color; granular or sugary feeling masses.

Plagioclase feldspar var. Labradorite: Iridescent, dark gray; striations on cleavage faces; harder than glass.

Plagioclase feldspar var. Albite: White to grey; striations on cleavage faces; harder than glass.

Potassium feldspar: Commonly beige to pink or reddish, however **Amazonite** is blue-green; exsolution lamellae on cleavage faces; harder than glass.

Pyrite: Metallic, brassy gold, cubic shape common; green-black streak.

Pyroxene: Hardness value right around glass (~5.5-6); blocky green to black crystals common; two cleavage directions at 90°.

Quartz: Harder than glass; glassy look; crystal shape, hexagonal prismatic; many colors common.

Serpentine: Green, white, grey masses or fibrous. *Composes serpentinite, California's state rock!

Sulfur: Yellow color and streak; light heft; brittle.

Talc: Soft, greasy feel; pearly or dull luster common.

Topaz: Harder than glass (H=8); adamantine luster, crystal shape, hexagonal prismatic; many colors common.

Tourmaline: Crystals are long, slender to thick prismatic and columnar with a triangular cross-section; crystal faces may be striated. Color is commonly brown to black in color (Schorl), however, the pink version, watermelon tourmaline, can be found near San Diego, CA!

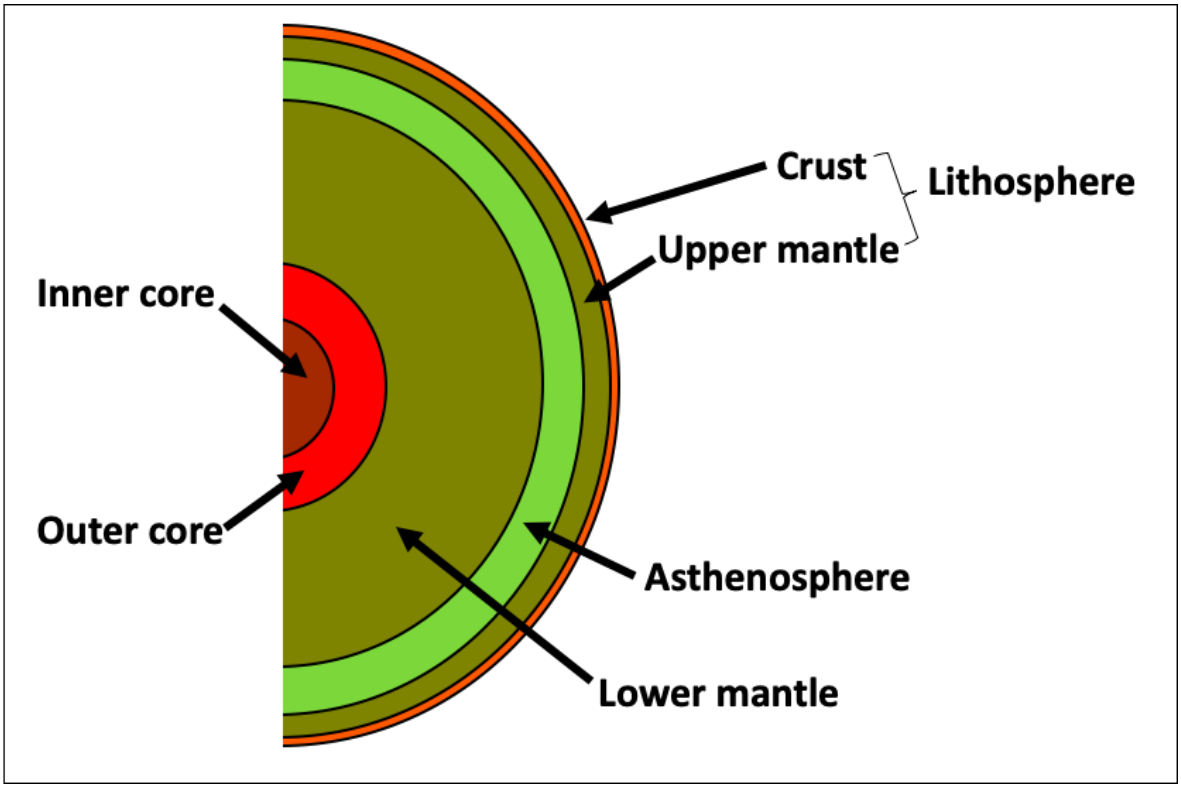
Chapter 4: The Internal Earth

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Analyze and compare properties, material, and layers within the Earth's geosphere

Thumbnail for Chapter 4:



Thumbnail: "The Layered Earth" (CC-BY 4.0; Chloe Branciforte, own work)

What's Under Our Feet?

Pop culture and Hollywood have journeyed to the center of the Earth several times; however, humans have never actually been there. We are not even able to see directly into the Earth's interior! Instead, geologists use evidence from **drilling**, proxies like **moon rocks** and **meteorites**, samples of the Earth's interior expelled by volcanoes (like **diamonds** and **peridotite**), seismic activity, and computer modeling to learn more about the composition and structure of Earth's interior.

Knowledge of the Earth's interior is the basis for geology and helps us understand the many processes operating inside and at the Earth's surface, notably **plate tectonics**. In this section, we will see how the Earth is structured, what its physical characteristics are, and how the internal structure of the Earth impacts us living on the surface.

Seismologists, geophysicists, volcanologists, and other disciplines may all study the internal Earth. Each branch uniquely investigates Earth's internal structure and the impacts that structure has on its internal and external workings. Like other geoscientists, interdisciplinary collaboration is common, with a strong influence from both math and technology sectors. Many of these geoscientists are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector, including in mining and natural resource extraction. Many of these career options require a college degree and postgraduate work. If you are interested in becoming a deep earth scientist, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

The Layered Earth

Before we can address plate tectonics, we must consider Earth's layered interior. At first glance, we can identify three major regions which are distinct based on their overall composition: the core, mantle, and crust. However, more layers are visible if we also consider mechanical properties of the layers. By examining these properties, five major layers are identified, the **lithosphere** (upper mantle and crust), **asthenosphere, lower mantle**, **outer core**, and **inner core**. For a visual journey through the interior of the Earth, visit the BBC's Journey to the Center of the Earth or watch this video and take a trip to the Earth's core.

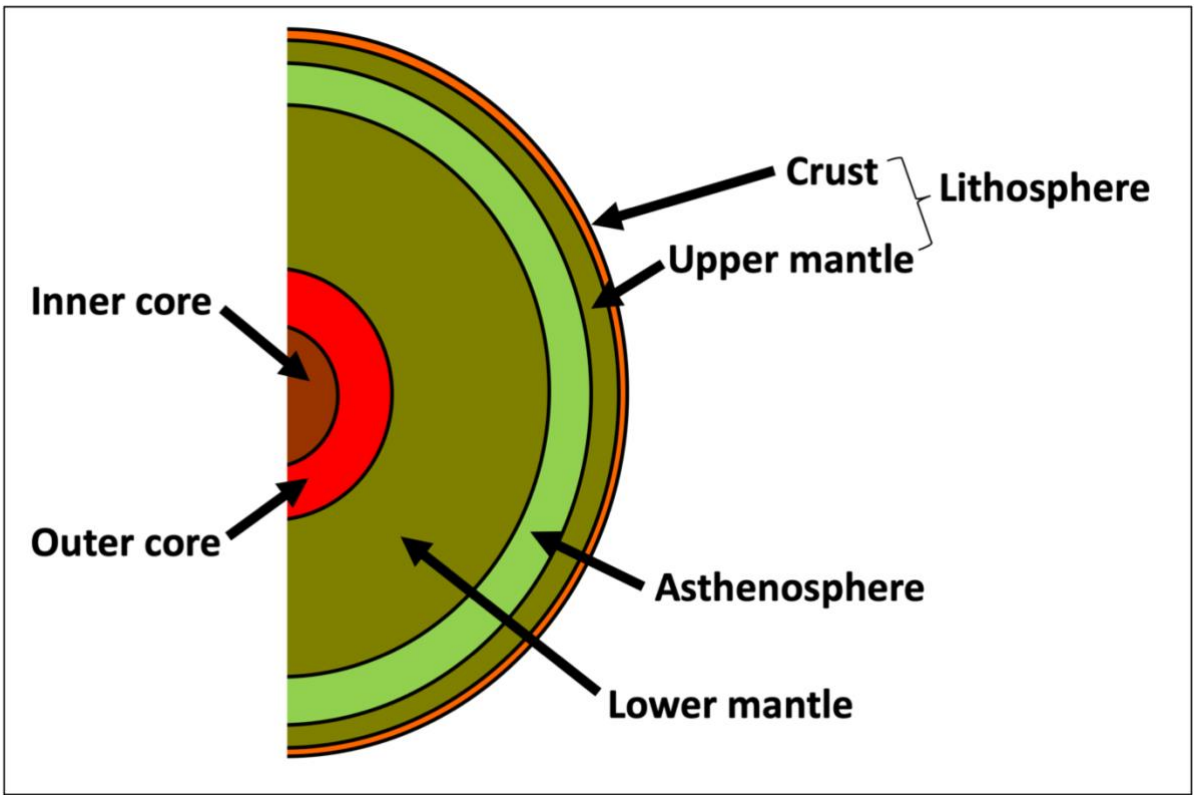


Figure 4.1: The Earth's layered structure.

Properties	**Lithosphere**	**Asthenosphere**	**Lower Mantle**	**Outer Core**	**Inner Core**
Physical behavior	Solid, rigid, brittle	Solid, plastic (ductile)	Solid, rigid, brittle	Liquid	Solid, rigid, not brittle
Overall Thickness (mi)	62	115	1,800	1,367	776

Table 4.1: The layers of the Earth have distinct and unique properties.

Attributions

- Figure 4.1: “The Layered Earth” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 4.1: “Properties of Internal Earth” (CC-BY 4.0; Chloe Branciforte, own work)

The Lithosphere

The **lithosphere**, which is composed of the **crust** and **upper mantle**, is about 100 km (~62 mi) thick and behaves as a brittle, rigid solid (**Figure 4.2**). This brittleness causes breaks (earthquakes) when stresses are applied. The crust is very thin relative to the radius of the planet; however, there are two distinct types: 1) **oceanic crust**, which is composed mainly of mafic igneous rocks like basalt and gabbro and 2) **continental crust**, which is composed mainly of the felsic igneous rock, granite. The two crustal types are very different and their density differences are significant to the mechanics of plate tectonics. Granite is much less dense than basalt, which results in a buoyant continental crust that sits higher on the underlying mantle. The denser and less buoyant oceanic crust sinks further into the underlying mantle, forming basins, many of which are filled with the Earth's oceans. **Table 4.2** highlights crustal differences in more detail.

Crustal type	Average thickness	Density	Composition	Dominant rock type
Oceanic	7 km	3.0 g/cm^3	Mafic	Basalt and gabbro
Continental	30 km	2.7 g/cm^3	Felsic	Granite

Table 4.2: The major differences between the oceanic and continental crust.

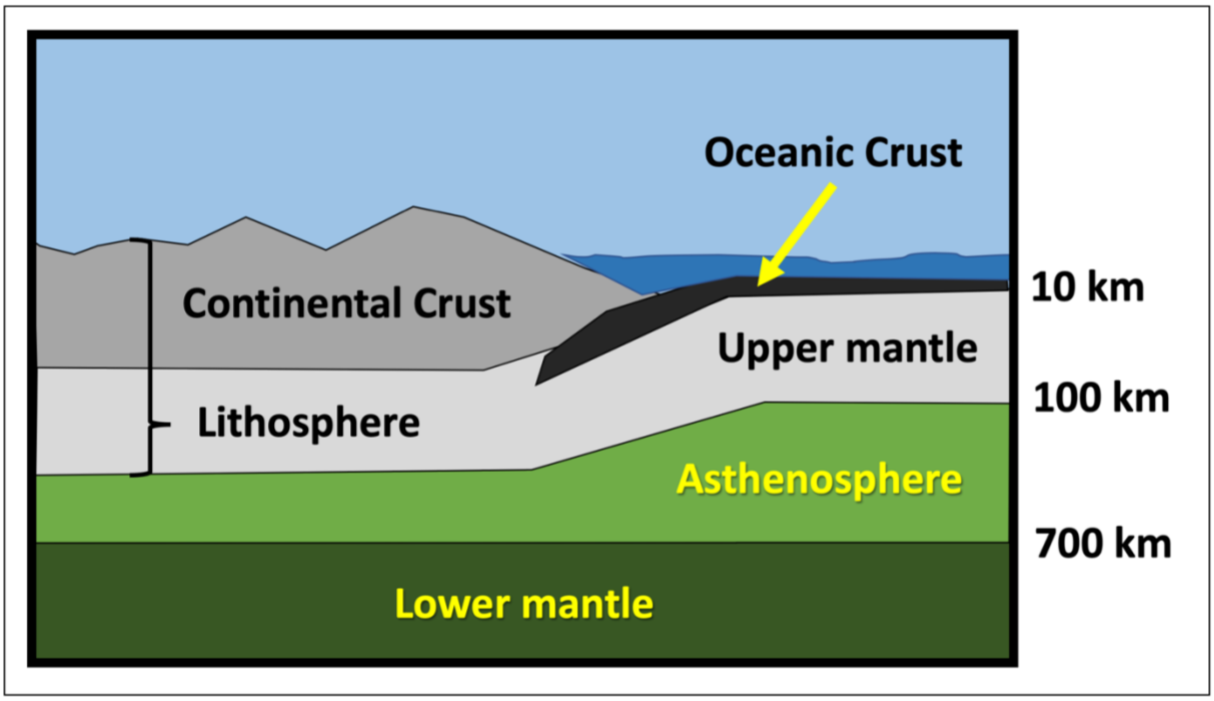


Figure 4.2: Components of the lithosphere, including the continental crust, oceanic crust, and upper mantle.

Attributions

- Table 4.2: “Crustal Types” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 4.2: “The Lithosphere” (CC-BY 4.0; Chloe Branciforte, own work)

The Mantle

The **mantle** is made of hot, solid rock, much of which is composed of **silicate minerals** such as **olivine**. The **asthenosphere**, a region of the mantle that is plastic and capable of flow, is likely composed mainly of the ultramafic rock **peridotite**. The **lower mantle** (mesosphere) is more rigid and rocky and is composed of different silicate minerals, such as **bridgmanite**.

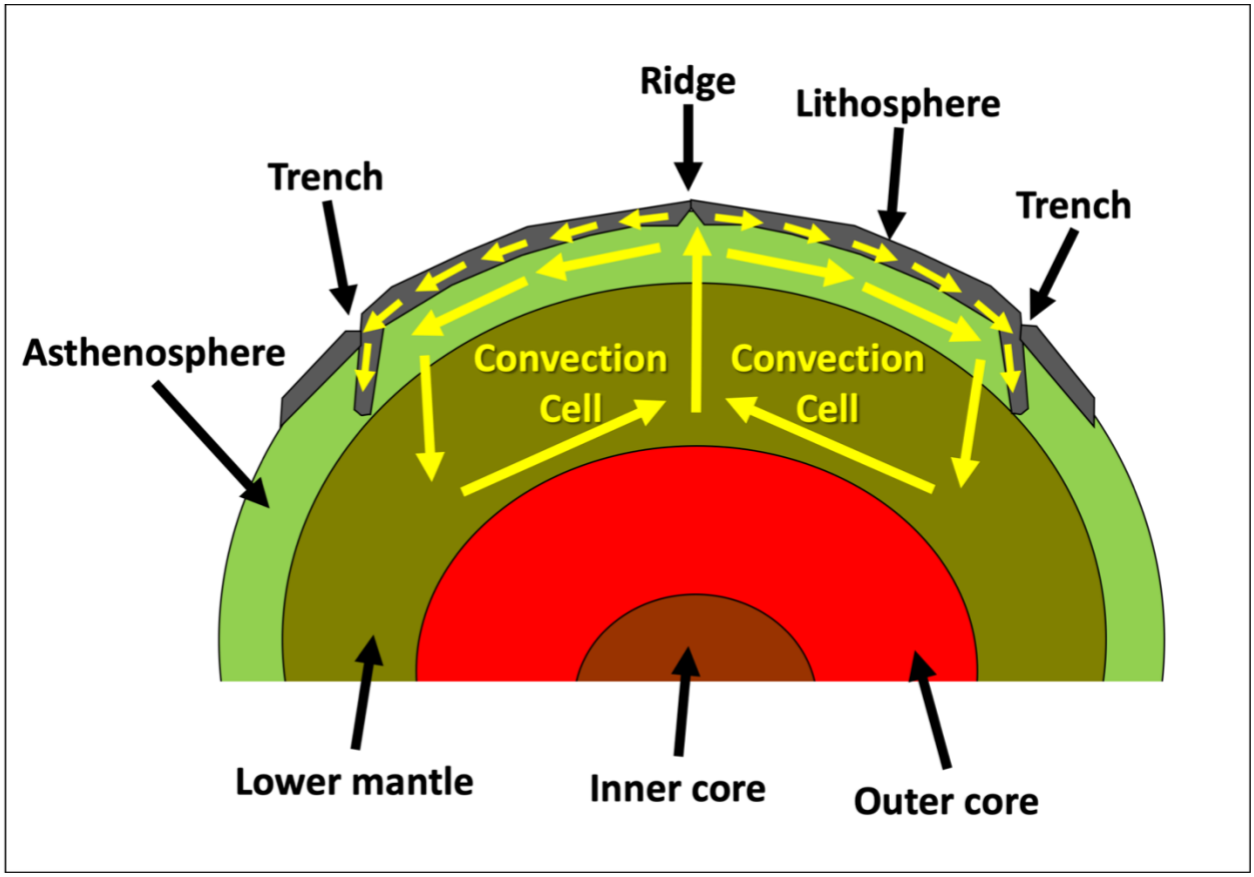


Figure 4.3: The convection cells of the mantle.

Convection currents, important to the mechanics of plate tectonics, develop as lower mantle materials near the core heat up. These **mantle convection cells** occur as particles in the rock begin to move more rapidly, decrease in density, rise toward the surface of the Earth. When the warm material reaches the surface, it spreads horizontally and begins to cool. Eventually the material becomes cool and dense enough to sink back down into the mantle toward the core. As the material sinks back to the bottom of the mantle, the material travels horizontally and the process begins again (**Figure 4.3**).

Attributions

- Figure 4.3: “Convection” (CC-BY 4.0; Chloe Branciforte, own work)

The Core

At the planet's center lies the **core**, which is dense and metallic. Calculations indicate that the core is about 85% iron metal with nickel metal making up most of the remaining 15%. Geologists know the core is metal because of proxies, like metallic meteorites, and from calculations of the overall density of the planet. Moving deeper into the interior of the Earth, temperature and pressure increase. Although the **inner core** is very hot (5200°C or 9392°F), it is solid because it is experiencing very high pressure (3.6 million atm). The pressure in the **outer core** is not high enough to keep it solid. Much of the heat here is produced by the breakdown of radioactive elements in the inner core.

Earthquake waves are used by geologists to "see" Earth's internal structure, similar to how a doctor uses a CT scan to look inside your body. This imaging of the Earth's interior by earthquake waves is **seismic tomography**, which highlights distinct boundaries, or **discontinuities**, between layers, where composition and matter changes occur. Because the inner core of the Earth is a solid metallic sphere made mostly of iron and nickel and surrounded entirely by liquid, we can visualize it as a giant ball bearing spinning in a pressurized fluid. Seismic tomography of the inner core has found evidence that it is spinning - rotating - just slightly faster than the rest of the Earth.

Earth's **magnetosphere** is produced by the interaction of the rapidly rotating solid inner core and the convection and electrically-charged nature of the liquid outer core (the **geodynamo**). This causes instability, and every several hundred thousand to several million years, Earth's magnetic field becomes unstable to the point that it temporarily shuts down. When it restarts, its north and south magnetic poles switch; this is called a **magnetic reversal**.

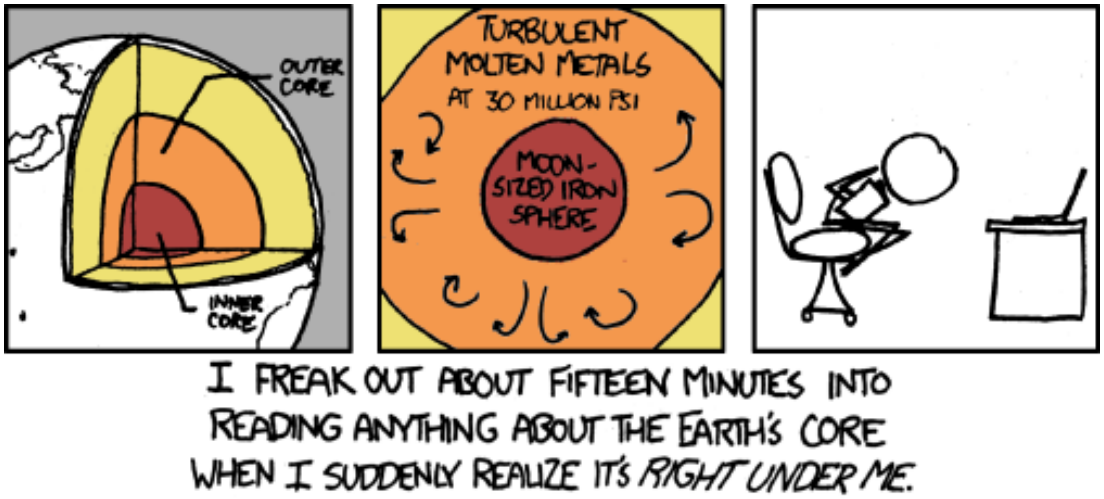


Figure 4.4

Attributions

- Figure 4.4: “Core” (CC-BY-NC 2.5; xkcd via xkcd.com)

Activity 4A: The Structure of Internal Earth

1. Label each layer at their correct letter, then color the layers using the following colors,
    - **Asthenosphere** - Light green
    - **Continental crust** - yellow
    - **Inner core** - red
    - **Lithosphere** - gray
    - **Mantle** - label, but do not color
    - **Mesosphere** - dark green
    - **Oceanic crust** - black
    - **Outer core** - orange

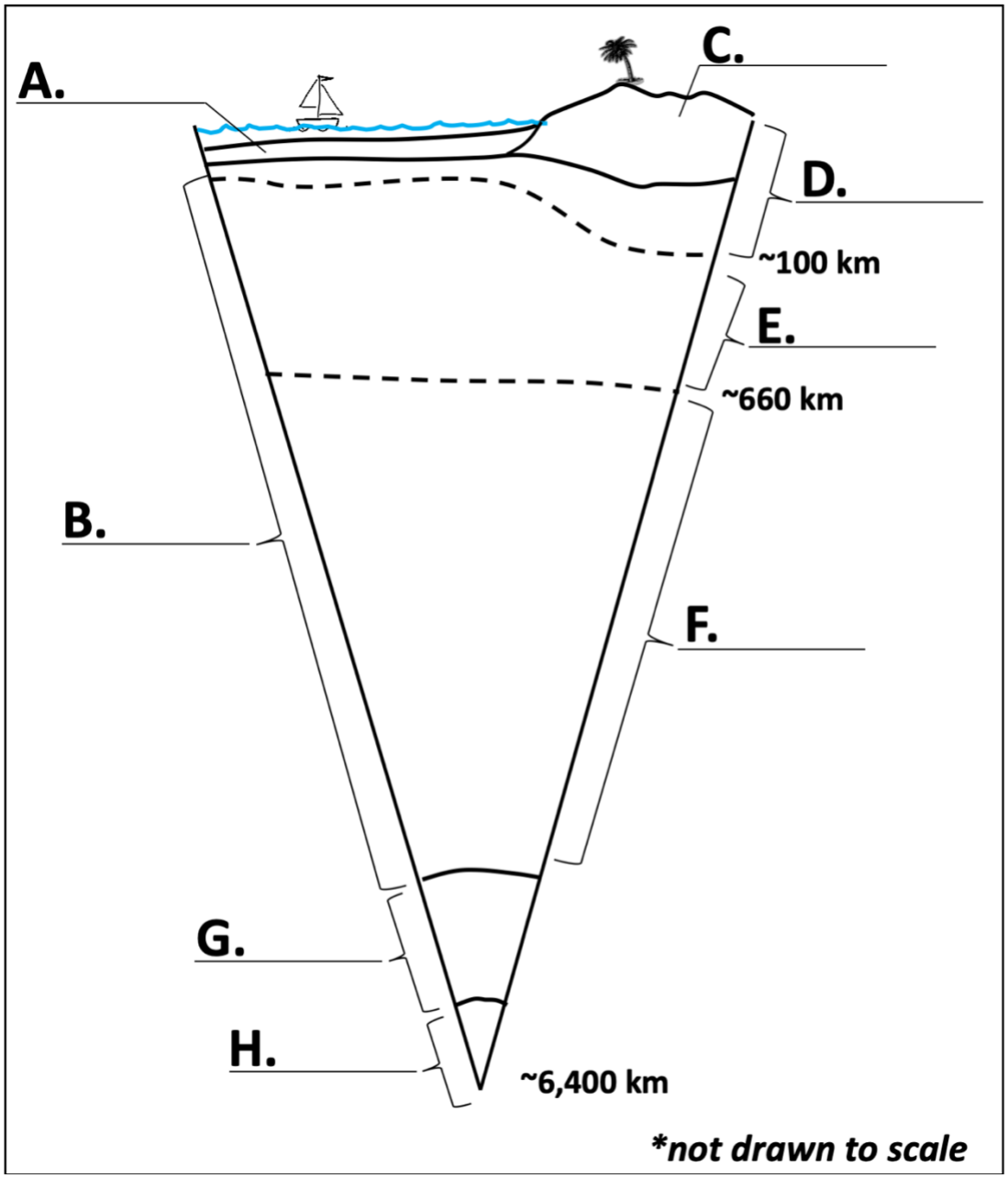


Figure 4.5: A cross-section of Earth to label.

Attributions

- Figure 4.5: “Cross-section of Earth” (CC-BY 4.0; Chloe Branciforte and Cynthia Lampe, own work)

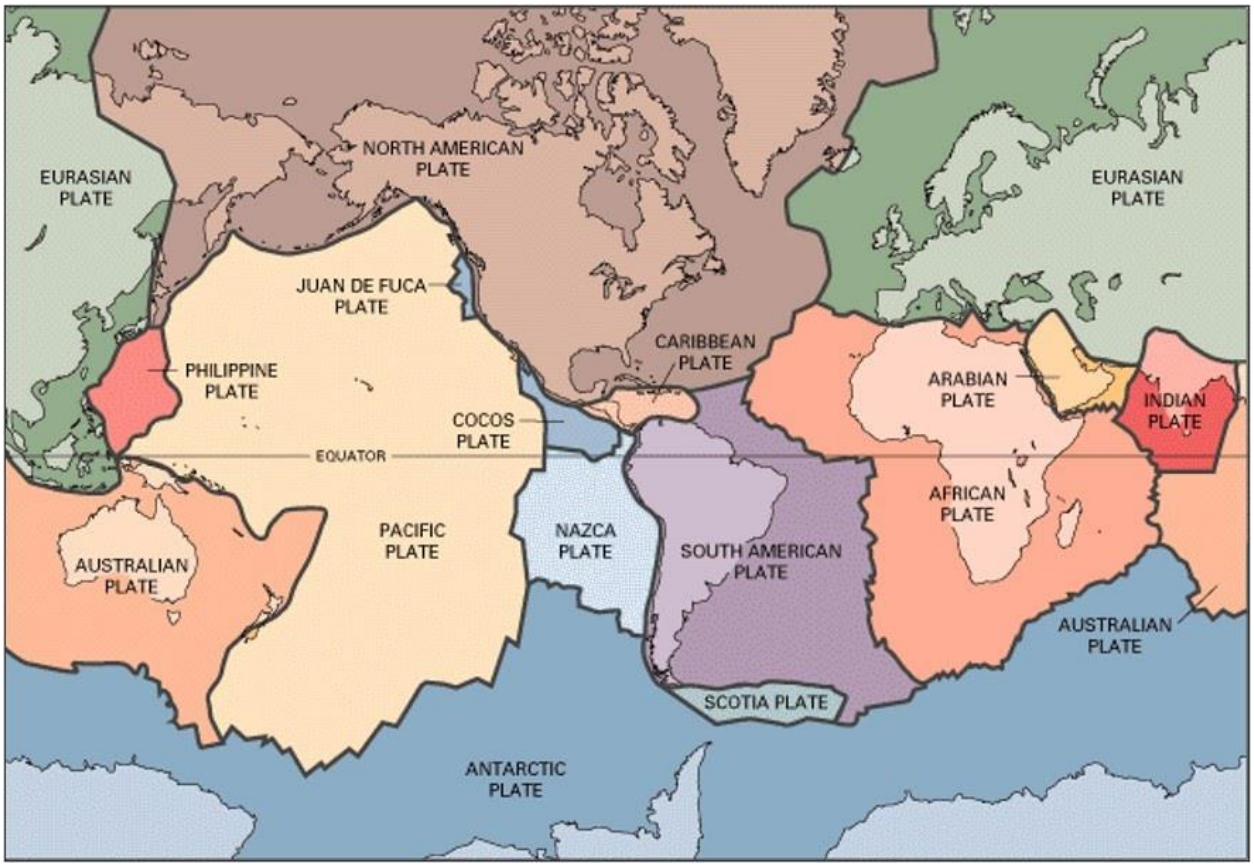
Chapter 5: Plate Tectonics

Learning Outcomes

After completing this chapter, you should be able to:

- ✓ Describe the progression of a Hawaiian Island and how it relates to the Theory of Plate Tectonics.
- ✓ Describe the properties of tectonics plates and how that relates to the proposed mechanisms driving plate tectonics.
- ✓ Be able to describe and identify the features that occur at different plate boundaries.

Thumbnail image for Chapter 5:



Thumbnail: "Tectonic Plates of the Earth" (Public Domain; USGS)

The Grand Unifying Theory of Geology

Recall in the scientific method the exact meaning of a **theory**: a well-supported explanation for a natural phenomenon that still cannot be completely proven. A **Grand Unifying Theory** is a set of ideas that is central and essential to a field of study such as the theory of gravity in physics or the theory of evolution in biology. The Grand Unifying Theory of geology is **Plate Tectonics**, which defines the outer portion of the earth as a brittle outer layer that is broken into moving pieces called **tectonic plates** (**Figure 5.1**). This theory is supported by many lines of evidence including the shape of the continents, the distribution of fossils and rocks, the distribution of environmental indicators, as well as the location of mountains, volcanoes, trenches, and earthquakes. The movement of plates can be observed on human timescales and easily measured using GPS satellites.

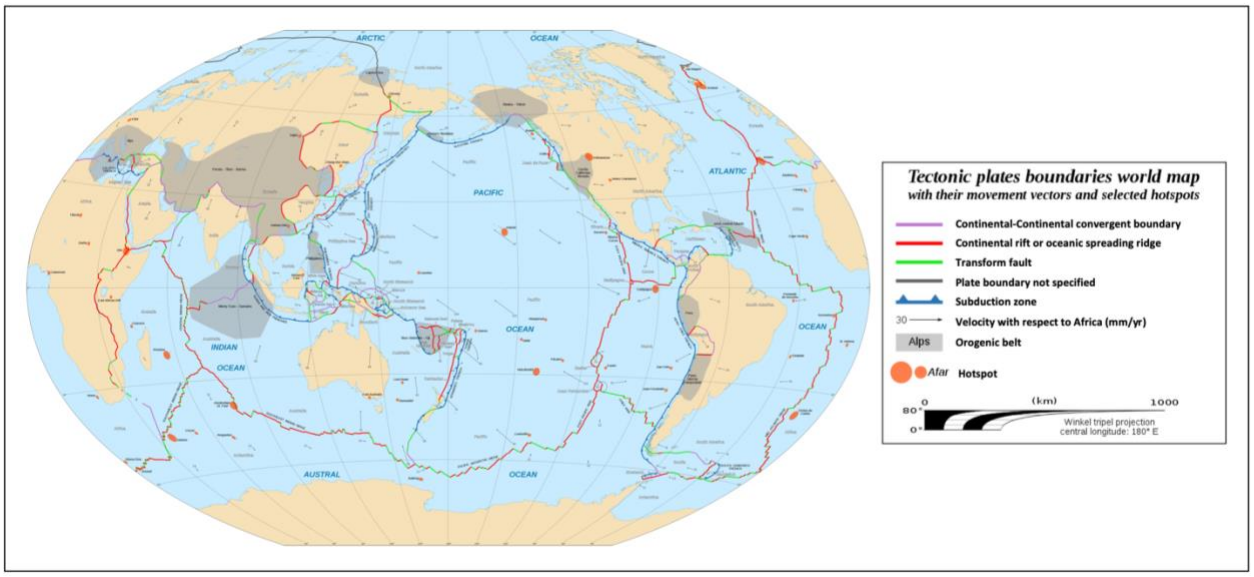


Figure 5.1: Tectonic plate boundaries world map with their movement vectors and selected hotspots.

Plate tectonics is integral to the study of geology because it aids in reconstructing earth's history. This theory helps to explain how the first continents were built, how oceans formed, and even helps inform hypotheses for the origin of life. The theory also helps explain the geographic distribution of geologic features such as mountains, volcanoes, rift valleys, and trenches. Finally, it helps us assess the potential risks of geologic catastrophes such as earthquakes and volcanoes across the earth. The power of this theory lies in its ability to create testable hypotheses regarding Earth's history as well as predictions regarding its future.

Seismologists, geophysicists, volcanologists and other disciplines may all study plate tectonics. Each branch uniquely investigates the topic, and may explore current tectonics, or the tectonics of ancient (or future) Earth. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many of these geoscientists are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including in mining and natural resource extraction. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 5.1: Derivative of “Tectonic Plate Boundaries World Map” (CC-BY-SA 3.0; Eric Gaba (Sting) via Wikimedia Commons) by Chloe Branciforte

Evidence of Moving Continents

The idea that the continents appear to have been joined based on their shapes is not new; in fact, this idea first appeared in the writings of **Sir Francis Bacon** in 1620. The resulting hypothesis from this observation is rather straightforward: the shapes of the continents fit together because they were once connected and have since broken apart and moved. This hypothesis refers to a historical event and cannot be directly tested without a time machine (and we don't have those yet). Therefore, geoscientists reframed the hypothesis by assuming the continents used to be connected and asking what other patterns we would expect to find.

This is exactly how turn of the century earth scientists, such as **Alfred Wegener**, addressed this important scientific question. Wegener compiled rock types, fossil occurrences, and environmental indicators within the rock record on different continents that appear to have been joined in the past, focusing mainly on Africa and South America; he found remarkable similarities across the continents! Other scientists followed suit and the scientific community was able to compile an extensive dataset that indicated that the continents were linked in the past in a supercontinent called **Pangaea** (named by Wegener) and have shifted to their current position over time. Dating these rocks using both relative and absolute methods allowed scientists to better understand the rate of motion, which has assisted in trying to determine the mechanisms that drive plate tectonics.

What Is a Tectonic Plate and What Are They Made From?

Many different lines of evidence suggest tectonic plates are moving. To build a theory, scientists need an explanation or a mechanism to explain the observed patterns. The theory of plate tectonics states that the outer rigid layer of the earth, the **lithosphere**, is broken into pieces called **tectonic plates** (**Figure 5.2**), and that these plates move independently above the flowing plastic-like portion of the mantle, the **asthenosphere**.

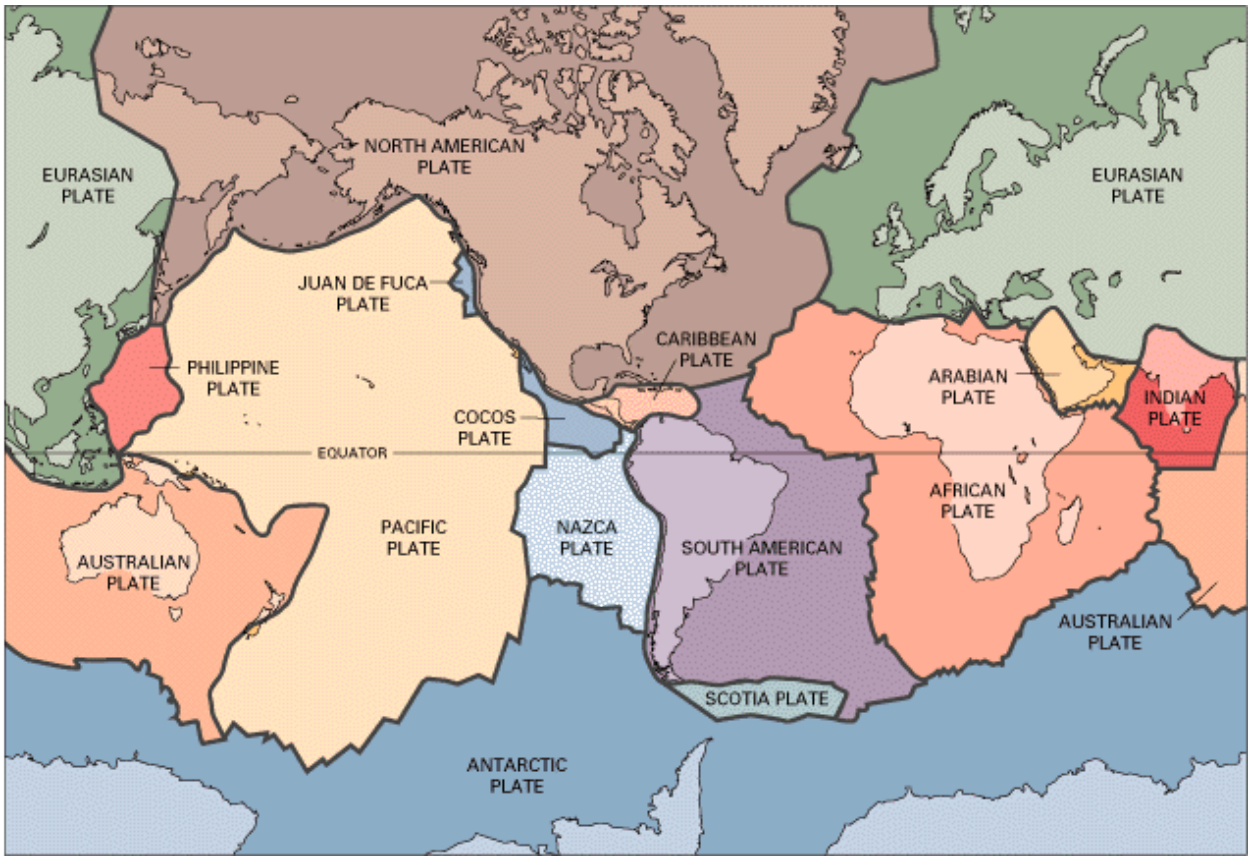


Figure 5.2: The tectonic plates divide the Earth's crust into distinct "plates" that are always slowly moving. Earthquakes are concentrated along these plate boundaries.

Tectonic plates are composed of the **lithosphere**: the crust and uppermost mantle that functions as a brittle solid. These plates are composed of oceanic crust, continental crust or a mixture of both. **Oceanic crust** is thinner and normally underlies the world's oceans, while the **continental crust** is thicker and, as its name implies, consists of the continents. The interaction of these tectonic plates is at the root of many geologic events and features, such that we need to understand the structure of the plates to better understand how they interact. The interaction of these plates is controlled by the relative motion of two plates (moving together,

apart, or sliding past) as well as the composition of the crustal portion of the plate (continental or oceanic crust).

Continental crust has an overall composition similar to the igneous rock **granite**, which is a solid, silica-rich crystalline rock typically consisting of a mixture of pink (feldspar), milky white (feldspar), clear (quartz), and black (biotite) minerals. Oceanic crust is primarily composed of the igneous rock **basalt**, which is a solid, iron and magnesium-rich crystalline rock consisting of a mixture of black and dark gray minerals (pyroxene and feldspar). The difference in rock composition results in distinctive physical properties that you will determine in the next set of questions (**Table 5.1**).

Crustal Properties	Continental Crust	Oceanic Crust
Composition	Granite	Basalt
Relative thickness	Thick	Thin
Relative age	Old	Young
Relative density	Less dense	More dense
Relative buoyancy	More buoyant	Less buoyant

Table 5.1: Major differences between continental and oceanic crust.

The age of the oceanic crust has been determined by systematically mapping variations in the strength of the Earth's magnetic field across the sea floor and comparing the results with our understanding of the record of Earth's **magnetic field reversal chronology** for the past few hundred million years. The ages of different parts of the crust are shown in **Figure 5.3**. The oldest oceanic crust is around 340 Ma (read "million years") in the eastern Mediterranean, and the oldest parts of the open ocean are around 180 Ma on either side of the North Atlantic. It may seem surprising, considering that parts of the continental crust are close to 4.0 Ga (read "billion years") old, that the oldest seafloor is less than 400 Ma. Of course, the reason for this is that all older seafloor has been either subducted or pushed up to become part of the continental crust. As one would expect, the oceanic crust is very young near the spreading ridges, and there are obvious differences in the rate of sea-floor spreading along different ridges. The ridges in the Pacific and southeastern Indian Oceans have wide age bands, indicating rapid spreading (approaching 10 cm or 3.9 inches per year) on each side in some areas, while those in the Atlantic and western Indian Oceans are spreading much more slowly (less than 2.5 cm or less than an inch per year).

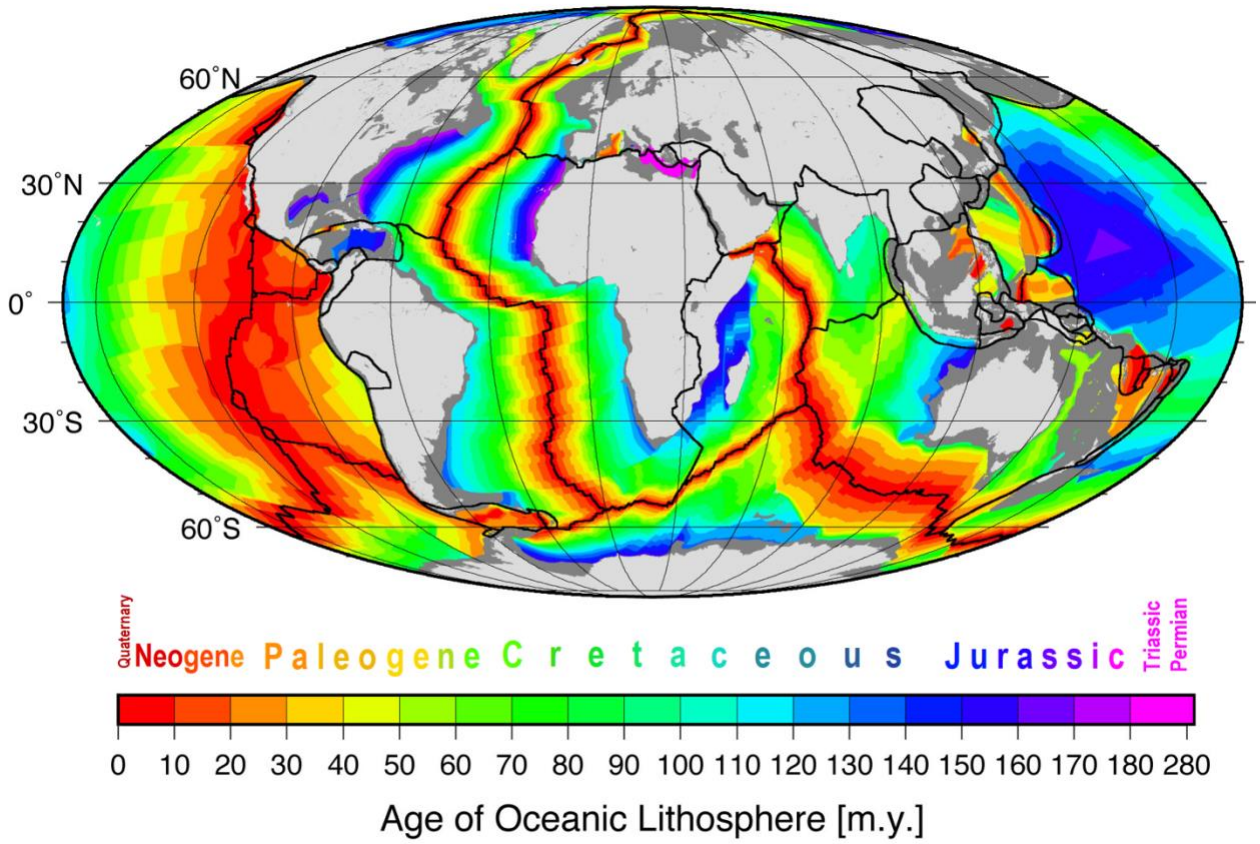


Figure 5.3: Age, spreading rates, and spreading symmetry of the world's oceanic crust.

Attributions

- Figure 5.2: “Tectonic Plates of the Earth” (Public Domain; USGS)
- Table 5.1: “Crustal Properties” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 5.3: “Age of Oceanic Lithosphere” (CC-BY 3.0; Müller, R.D., M. Sdrolias, C. Gaina, and W.R. Roest via Wikimedia Commons)

Types of Plate Boundaries

Tectonic plates can interact in three different ways: they can come together, they can pull apart, or they can slide by each other (**Figure 5.4**). The other factor that can be important in the interaction is the composition of the plates (oceanic or continental crust). These three types of motions along with the type of plates on each side of the boundary can produce vastly different structures and geologic events.

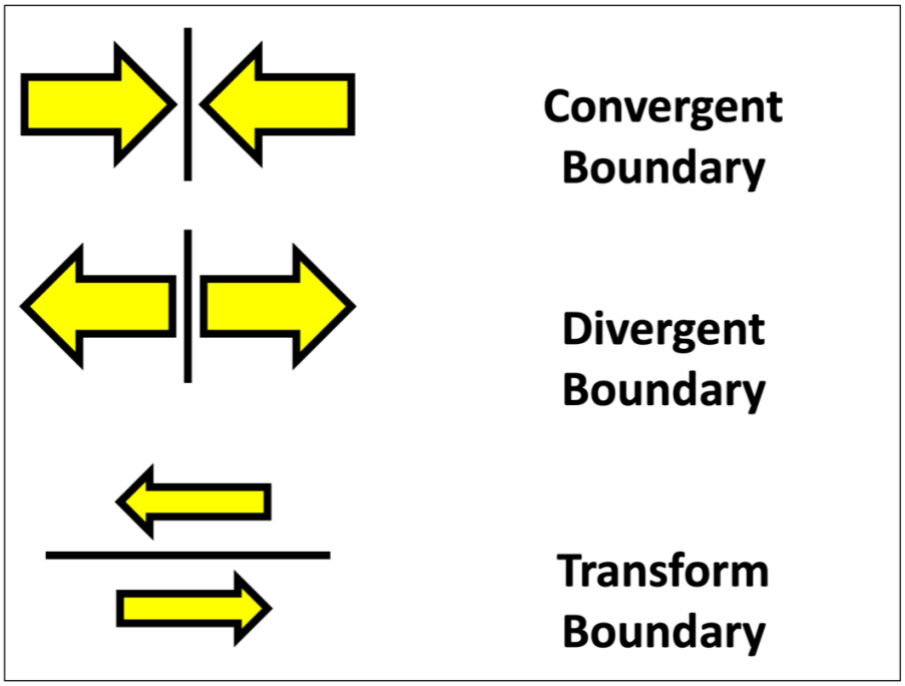


Figure 5.4: The major plate boundaries and their associated movement.

Divergent Boundaries

Two plates that are moving apart from each other are referred to as diverging. **Divergent boundaries** (**Figure 5.5**) are important because they split continents apart, breaking them into separate plates, and they serve as the site for the formation of new oceanic crust. In a **continental rift**, a divergent boundary forms within a continent and the region stretches apart. As the area is stretched, the resulting crust becomes thinner and a topographic low or valley is formed (such as the East African Rift Valley). This extension is not a smooth process, so the area is prone to earthquakes and volcanic activity. Eventually, the crust becomes so thin it will rupture and form a gap between the plates, which will fill with molten rock, forming new oceanic crust. This new, thin, and dense plate is topographically low and will eventually become covered in seawater, forming a narrow, elongate (linear) sea (such as the Red Sea). These continental rift zones eventually evolve into **mid-ocean ridges** (MORs).

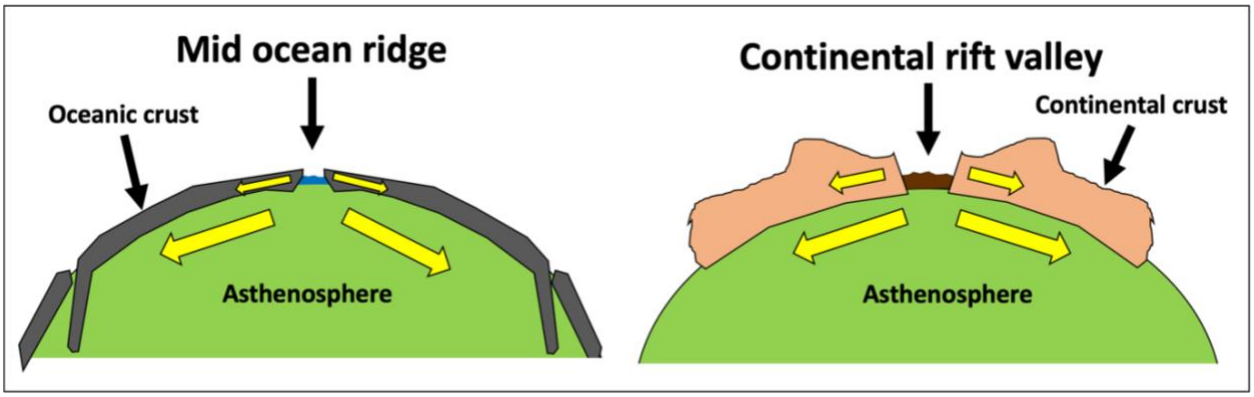


Figure 5.5: Development of a mid-ocean ridge and continental rift valley.

Convergent Boundaries

Two plates that are moving together are referred to as converging. **Convergent boundaries** are important because they typically join (suture) continents together to form larger plates as well as where ocean crust is destroyed. The resulting structures we see at convergent boundaries depend on the types of tectonic plates. In a **continent-continent convergent plate boundary** (**Figure 5.6**), two thick, low density continental plates converge resulting in a large collision which produces mountains. This is a violent process resulting in earthquakes, deformation (folds and faults) of rock, intense heat and pressure, and the uplift of mountains (an **orogeny**).

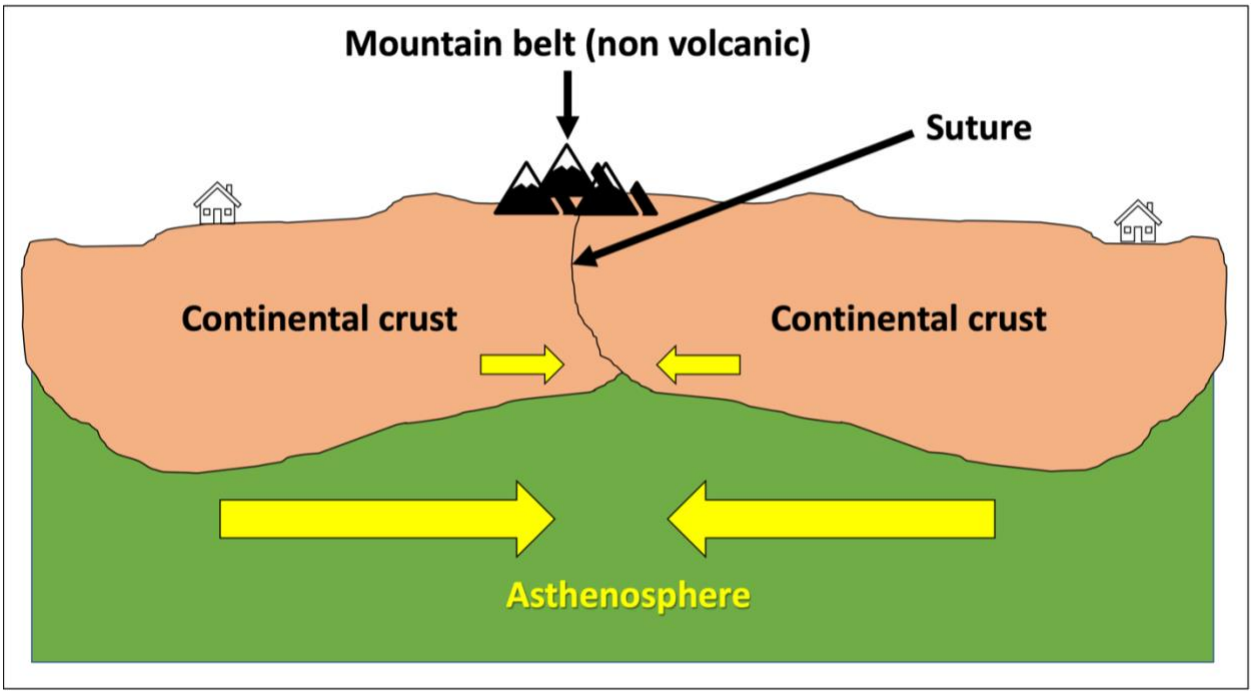


Figure 5.6: Mountains are produced when continental crustal slabs collide.

If a continental plate and an oceanic plate converge (continent-ocean convergent plate boundary) (Figure 5.7) the resulting process is subduction, the oceanic plate sinks downward toward the mantle underneath the continental plate. This produces several distinct features including a deep ocean trench, abundant earthquakes, and a line of volcanoes along the margin of the continent (continental volcanic arc). Associated with subduction zones is the Wadati-Benioff zone, a zone where earthquakes are produced; this zone ranges in depth from shallow (at the trench) to deep (~600km), indicating that the oceanic plate is sinking into the mantle.

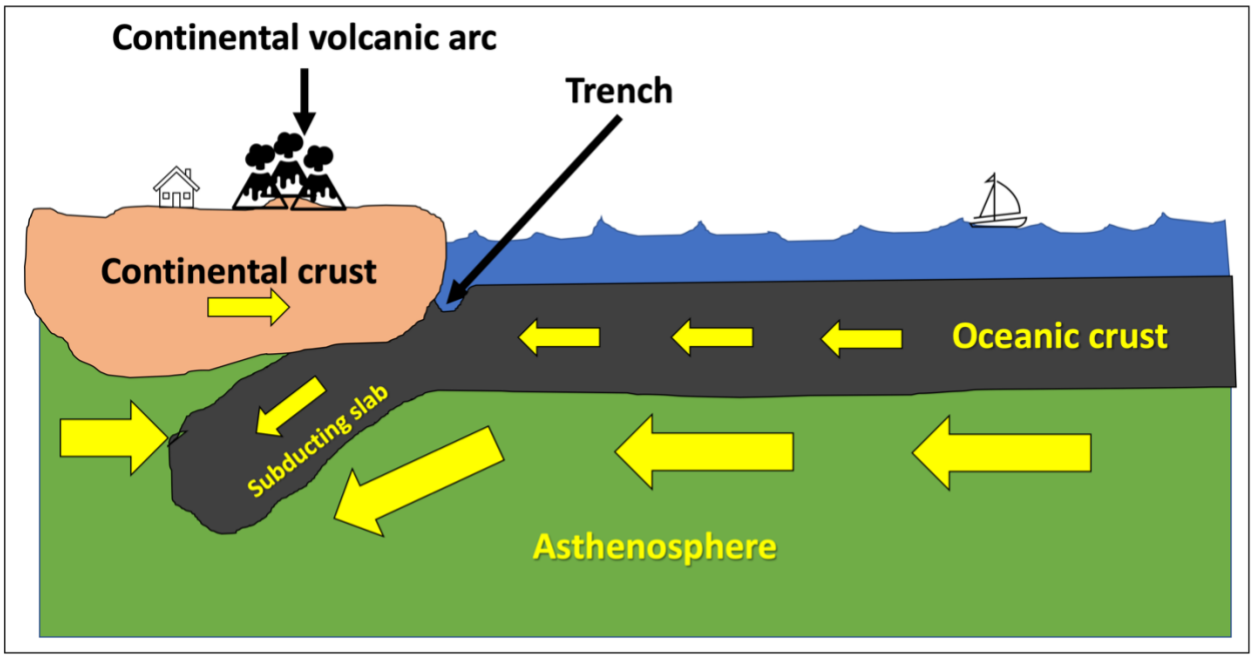


Figure 5.7: Volcanic mountains are produced on a continent when oceanic crust subducts.

If two oceanic plates converge (ocean-ocean convergent plate boundary) (Figure 5.8) it will also result in **subduction** with deep ocean trenches, abundant earthquakes, and volcanoes. However, the volcanoes will appear on an oceanic plate and will form islands along the tectonic boundary (volcanic island arc).

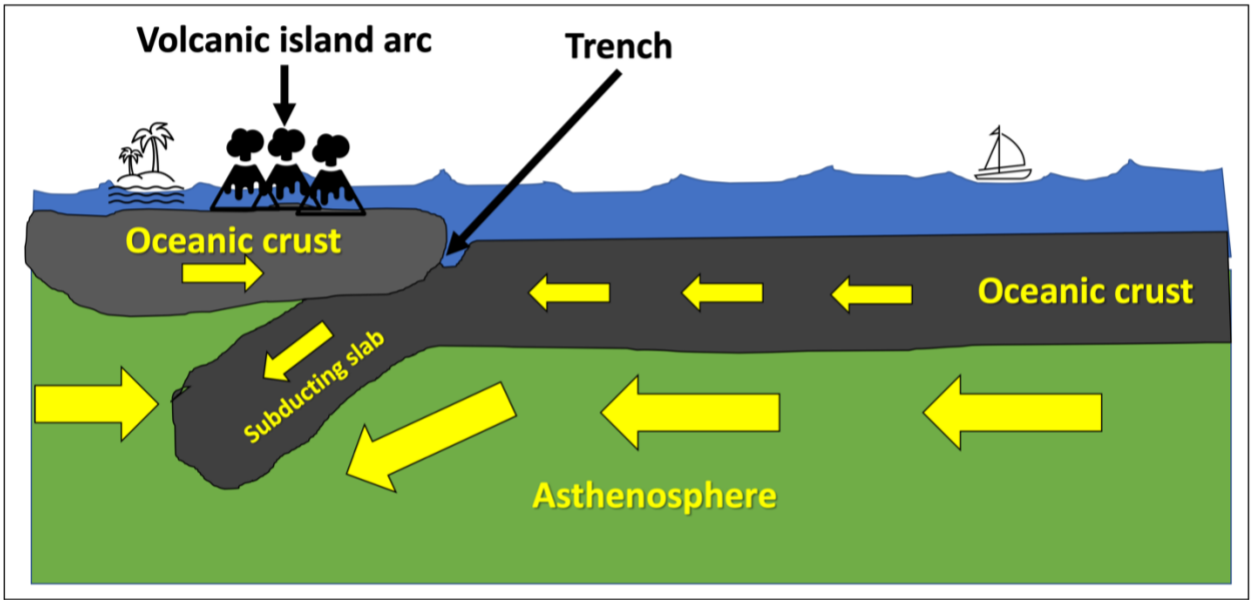


Figure 5.8: Volcanic island mountains are produced when oceanic crust subducts.

Transform Boundaries

When the two plates slide past each other it is called a transform boundary. This type of boundary differs from others in that no new crust is being formed and no old crust is being destroyed. Transform boundaries are often marked by abundant earthquakes that can be close to the surface as well as distinctive patterns of rivers that become offset as the land is moving underneath them. The most famous transform boundary is the San Andreas Fault (Figure 5.9). Some transform boundaries are located on the ocean floor and associated with mid-ocean ridges.

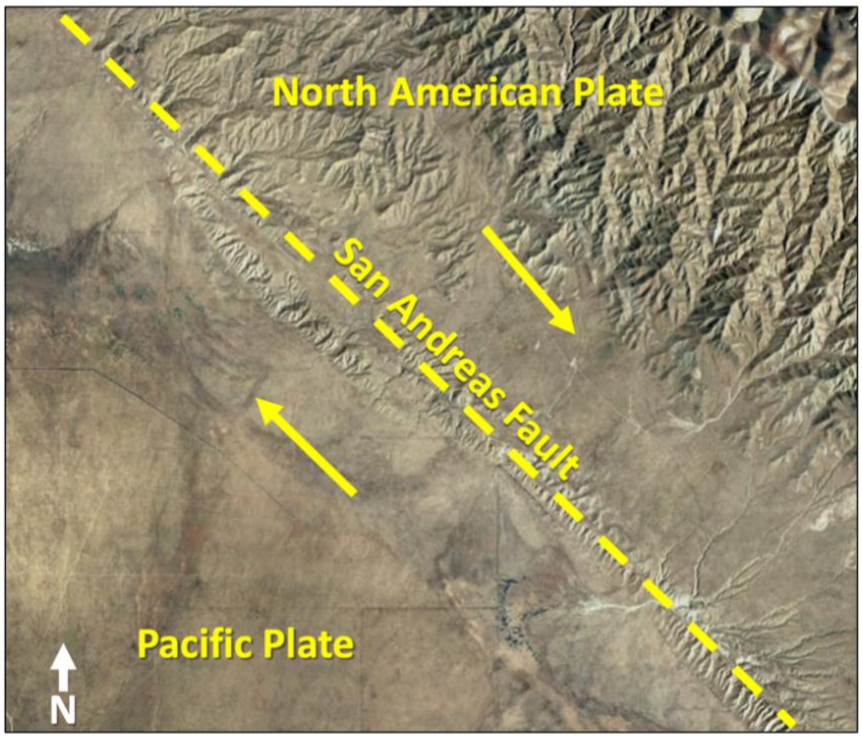


Figure 5.9: Map view of the San Andreas Fault, with the North American Plate moving to the southeast and the Pacific Plate moving to the northwest.

Boundary Type	Plate Compositions	Earthquake Depth	Change in Crust	Identifying Features	Geologic Phenomena
Divergent continental rift	Continent-Continent	Shallow	Formation of rift valley	Rift valley and volcanoes	Volcanoes, Earthquakes
Divergent mid-ocean ridge	Ocean-Ocean	Shallow	Formation of new oceanic crust	Submarine mountains	Submarine Volcanic Activity, Earthquakes
Convergent collision zone	Continent-Continent	Shallow to intermediate	Metamorphism & folding of the crust	Mountains	Earthquakes
Convergent subduction zone	Continent-Ocean	Shallow to deep	Partial melting of the oceanic crust as it is subducted	Trenches, continental volcanic arcs	Volcanoes, Earthquakes, Tsunamis
Convergent subduction zone	Ocean-Ocean	Shallow to deep	Partial melting of the oceanic crust as it is subducted	Trenches, volcanic island arcs	Volcanoes, Earthquakes, Tsunamis
Transform	Continent-Continent	Shallow	No change	Offset rivers	Earthquakes
Transform	Ocean-Ocean	Shallow	No change	Associated with MORs	Earthquakes

Table 5.2: Summary table of plate boundaries and their associated geologic phenomena.

Attributions

- Figure 5.4: “General Plate Boundaries” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 5.5: “Rifting” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 5.6: “Convergence of the Continents” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 5.7: “Continental Volcanic Arc” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 5.8: “Volcanic Island Arc” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 5.9: “San Andreas Fault” (CC-BY 4.0; Chloe Branciforte using Google Earth, own work)
- Table 5.2: “Boundary Summary” (CC-BY 4.0; Chloe Branciforte, own work)

Plate Tectonic Mechanisms

The question still remains, *why do tectonic plates move*? The answer comes down to gravity and mantle convection. The mantle flows through time creating convection currents. These convection currents flow underneath the plates and through friction pull them along at the surface as well as when they are subducted which is a force called slab suction. Related to this force is **slab pull**, which is a gravitational force pulling the cold subducting plate down into the mantle at a subduction zone. In addition, there is a force from potential energy at ocean ridges called **ridge push**. This is a gravitational force pushing down on the elevated ridge and because of the plate's curvature it results in a horizontal force pushing the plate along the earth's surface. These forces all occur deep inside the Earth and operate on very large geographic scales making them difficult to measure. There are several competing models for the mechanisms behind plate motion, such that there are still some areas of debate surrounding the mechanics of plate tectonics which is why Plate Tectonics is a scientific theory. Documenting an event is much easier and more straightforward than explaining why it occurred. Watch this Minute Earth video on Plate Tectonic mechanisms.

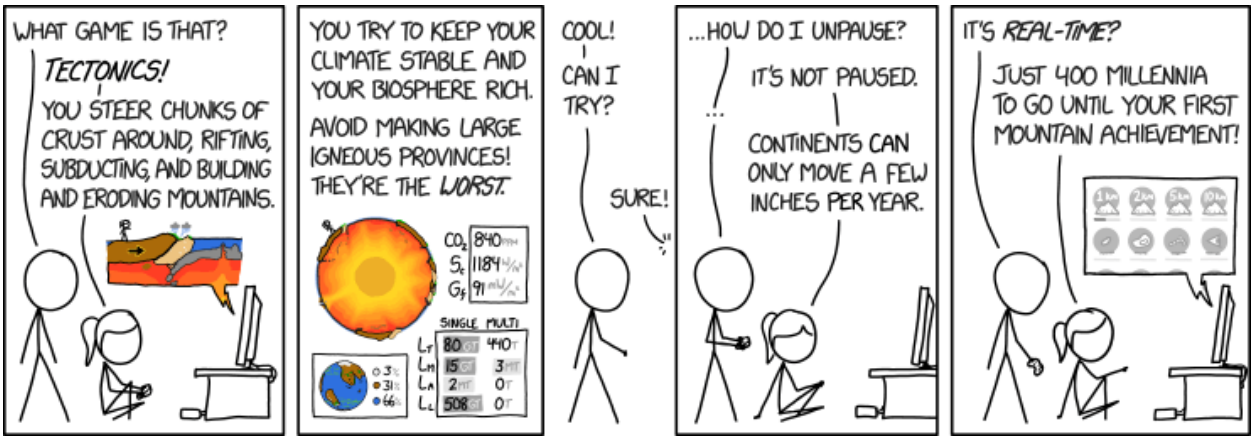


Figure 5.10

Attributions

- Figure 5.10: “Tectonics Game” (CC-BY-NC 2.5; xkcd via xkcd.com)

Activity 5A: Plate Motion and Evidence

One of the most striking things about the geography of the continents today is how they appear to fit together like puzzle pieces. The reason for this is clear: they once were connected in the past and have since separated shifting into their current positions.

Open the browser version of Google Earth and zoom out to an eye altitude (camera) of ~10,000 miles. Examine the coastlines of eastern South America and Western Africa and notice how well they match in shape. There are scientifically important rock deposits in southern Brazil, South America and Angola, Africa that show the northernmost glacial deposits on the ancient continent of Pangaea, which indicates these two areas were once connected.

1. Based on the shape of the two coastlines, give the present-day latitude and longitude of two sites along the coasts of these countries that used to be connected when the two continents were joined as a part of Pangaea (note: there are multiple correct answers):
    - **a.** Brazil:
        - **i.** Latitude:
        - **ii.** Longitude:
    - **b.** Angola
        - **i.** Latitude:
        - **ii.** Longitude:

2. Measure in centimeters the distance (Map Length) between the two points you recorded in the previous question. *Hint: use the ruler icon along the left-hand toolbar.*
    - **a.** Distance (in centimeters) =

3. This portion of Pangaea broke apart 200,000,000 years ago. Using the distance you measured above, calculate how fast (the rate) South America and Africa are separating in cm/year. (*Hint: the formula to use here is Rate= Distance/Time*). SHOW YOUR WORK.

Examine the Western Coast of South America, the Eastern Coast of Asia, and the Pacific Ocean. If South America and Africa are separating and the Atlantic Ocean is growing, then the opposite must be occurring on the other side of the earth (the Americas are getting closer to Asia and the Pacific Ocean is shrinking). It begs the question, when will the next supercontinent form? To determine this, we need a bit more information.

4. Measure the distance between North America and Mainland Asia in centimeters? (*Hint: measure across the Pacific at 40° N latitude, between Northern California and North Korea*)
    a. Distance (in centimeters) =

5. Using the distance above, and the rate calculated in question 3, determine the time it will take to develop a new supercontinent. (*Hint: the formula Rate= Distance/Time, can be reworked to Time = Distance/Rate*). SHOW YOUR WORK.

Activity 5B: Hot Spots

What Are Hot Spots?

In addition to GPS technology, geologists can also track plate motion using the location of hot spots, volcanically active areas on the Earth's surface that are caused by anomalously hot mantle rocks underneath (**Figure 5.11**). This heat is the result of a **mantle plume** that rises from deep in the mantle toward the surface resulting in the production of magma and volcanoes. These mantle plumes occur within the asthenosphere or deeper, such that they are unaffected by the movement of the continental or oceanic plates. Mantle plumes appear to be stationary through time; therefore, as the tectonic plate moves over the hot spot, a linear chain of volcanoes is produced. This gives geologists a wonderful view of the movement of a plate through time with the distribution of volcanoes indicating the direction of motion and their ages revealing the rate at which the plate was moving. Interested in hot spots? Want to learn more? Read this article from Earth Magazine: *The Question of Mantle Plumes*.

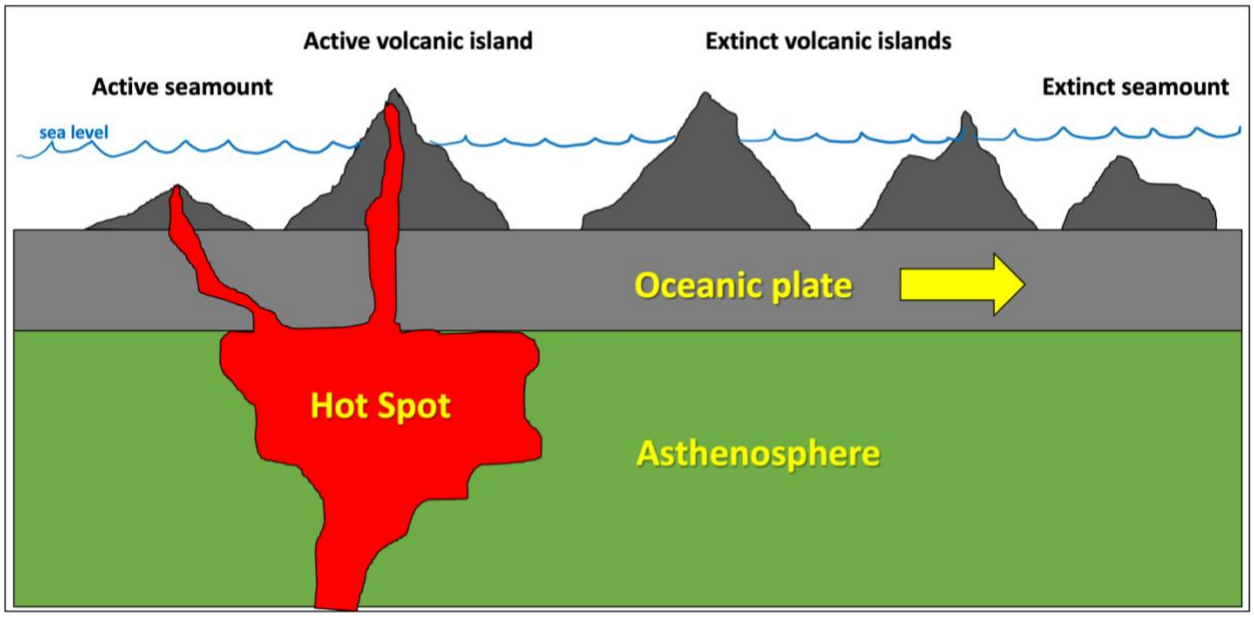


Figure 5.11: The life of an oceanic hot spot.

The Hawaiian Hot Spot

One of the most striking examples of a hot spot is underneath Hawaii. The mantle plume generates magma that results in an active volcano on the seafloor, referred to as a seamount. Each eruption causes the volcano to grow until it eventually breaks the surface of the ocean and forms a volcanic island. As the oceanic plate shifts the volcano off the stationary hot spot,

the volcano loses its source for magma and becomes inactive. The volcano then cools down, contracts, erodes, sinks slowly beneath the ocean surface, and is carried by the tectonic plate as it moves over time. As each island moves away from the mantle plume, a new island will then be formed at the hot spot in a continual conveyor belt of islands. Therefore, the scars of ancient volcanic islands near Hawaii give a wonderful view of the movement of the tectonic plate beneath the Pacific Ocean.

Open the browser version of Google Earth and type "Hawaii" into the search bar and zoom out to an eye altitude (Camera) of 700 miles. Examine the chain of Hawaiian Islands.

1. On the map of the Hawaiian Islands (**Figure 5.12**), include the following:
    - A North arrow
    - Label the following islands: Big Island of Hawaii, Kauai, Maui, Molokai, Oahu

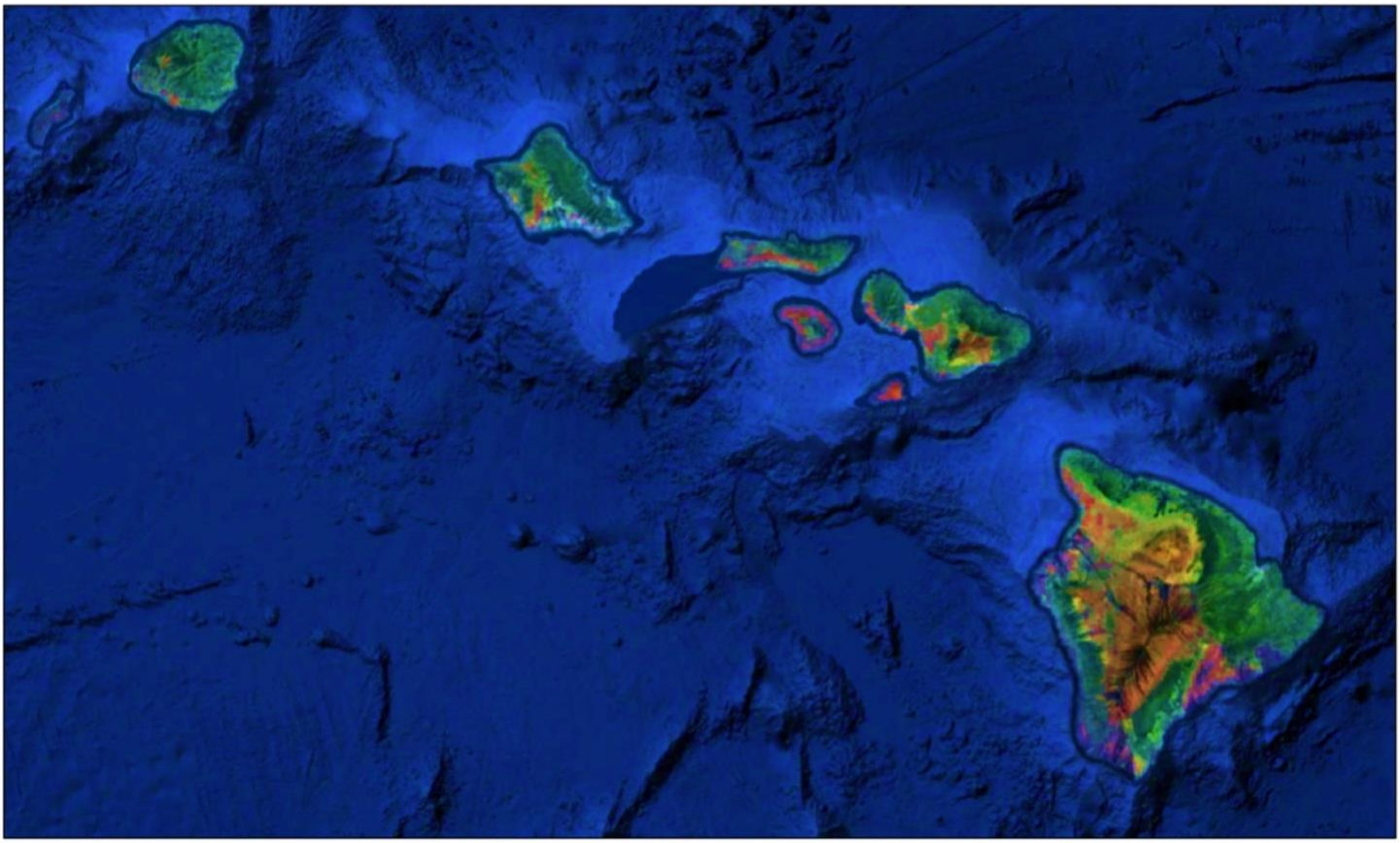


Figure 5.12: Map view of the Hawaiian Islands.

2. Next, label on the map the ages of each of the islands. These ages were determined through radiometric dating of the lava flows on the islands.
    - Big Island of Hawaii: 0 years old (Active)
    - Kauai: 5.1 million years old
    - Maui: 1.3 million years old
    - Molokai: 1.8 million years old
    - Oahu: 3.7 million years old

3. In Google Earth, measure the distance between the islands. To do this, measure from the center of each island and its adjacent island in centimeters. (*Hint: numbers will be large*)
    a. Distance between the Big Island and Maui (in cm):
    b. Distance between Maui and Molokai (in cm):
    c. Distance between Molokai and Oahu (in cm):
    d. Distance between Oahu and Kauai (in cm):

4. Look closely at each island in Google Earth and record the maximum elevation in centimeters. (*Hint: elevation can be determined by placing your cursor over a point and reading the elevation on the lower right of the image by the latitude and longitude. The elevation units can be changed in your settings. To locate the highest point on the islands, tilt the image or use the 3D button. Convert meters to centimeters by multiplying by 100.)*
    a. Big Island of Hawaii, max elevation (in cm):
    b. Kauai, max elevation (in cm):
    c. Maui, max elevation (in cm):
    d. Molokai, max elevation (in cm):
    e. Oahu, max elevation (in cm):

5. Consider the ages and positions of the islands listed above along with what you know about plate tectonics and hotspots. In what general direction is the Pacific Plate moving?
    a. Northwest
    b. Southeast
    c. Northeast
    d. Southwest

6. How fast was the Pacific plate moving during the last 1.3 million years between the formation of the Big Island and Maui? Calculate your answer in cm/year. (*Hint: Rate = Distance/Time*). SHOW YOUR WORK.

7. How fast was the Pacific plate moving between the formation of Oahu and Kauai? Calculate your answer in cm/year. (*Hint: Rate = Distance/Time*). SHOW YOUR WORK.

8. Zoom out and examine the dozens of sunken volcanoes, referred to as extinct seamounts, to the northwest of Niihau, these are named the Emperor Seamounts. As one of these volcanic islands on the Pacific Plate moves off the hotspot it becomes inactive, or extinct, and the island begins to sink as it and the surrounding tectonic plate cool down. The speed the islands are sinking can be estimated by measuring the difference in elevation between two islands and dividing by the difference in their ages. *Note, this method assumes the islands were a similar size when they were active.*
    a. Calculate how fast the Hawaiian Islands are sinking, by using the ages and elevations of Maui and Kauai. (*Hint: Rate = Distance/Time*). SHOW YOUR WORK.

b. When will the Big Island of Hawaii sink below the surface of the ocean? (*Hint:* use the rate calculated above, ignoring possible changes in sea level, and the max elevation of the Big Island in centimeters; Time = Distance/ Rate). SHOW YOUR WORK.

Attributions

- Figure 5.11: “Life of a Hotspot” (CC-BY 4.0; Chloe Branciforte and Cindy Lampe, own work)
- Figure 5.12: “Hawaiian Islands” (CC-BY 4.0; Chloe Branciforte using Google Earth, own work)

Activity 5C: Plate Densities

An important property of geological plates is their density. Remember the asthenosphere has fluid-like properties, such that tectonic plates 'float' relative to their density. This property is called **isostasy** and represents the equilibrium between crustal height and relative density. This is similar to buoyancy in water. For example, if a cargo ship has a full load of goods it will appear lower than if it were empty because the density of the ship is on average higher. Therefore, the relative density of two plates can control how they interact at a boundary and the types of geological features found along the border between the two plates.

Recall the Earth's crust is divided into two main types:

- **Continental crust**, which is composed of granite, is relatively older and thicker than oceanic crust. The thickness of the continental crust is between 25-70 km with an average thickness around **30 km**. The average density of granite is **2.75 g/cm^3** (read as 2.75 grams per cubic centimeter).
- **Oceanic crust**, which is composed of basalt, is relatively younger and thinner than continental crust. The thickness of the oceanic crust is between 5-10 km with an average thickness of **7 km**. The average density of basalt is **3.0 g/cm^3** (read as 3.0 grams per cubic centimeter).

1. Which crustal type is thicker?

2. Which crustal type is denser?

   a. How did you determine which crustal type was denser?

   b. Why do you think this is the case?

3. Which crustal type is more buoyant?

   a. How did you determine this?

Measuring the density of rocks is fairly easy and can be done by first weighing the rocks and then calculating their volume. The latter is best done by a method called **fluid displacement**

using a graduated cylinder. Water is added to the cylinder and the level is recorded, a rock is then added to the cylinder and the difference in water levels equals the volume of the rock.

Density is then calculated as the mass divided by the volume (Density = Mass/Volume).

Figure 5.13 contains the information needed to calculate density. There are four rocks which have weight (in grams) as well as the volume of water recorded by a graduated cylinder (in milliliters) before and after the rock was added.

Notes:

- *Each line on the graduated cylinder represents 10 milliliter (ml).*
- *When measuring volume, round to the nearest 10 ml line on the graduated cylinder.*
- *Surface tension will often cause the water level to curve up near the edges of the graduated cylinder creating a feature called a **meniscus**. To accurately measure the volume, use the lowest level the water looks to occupy.*

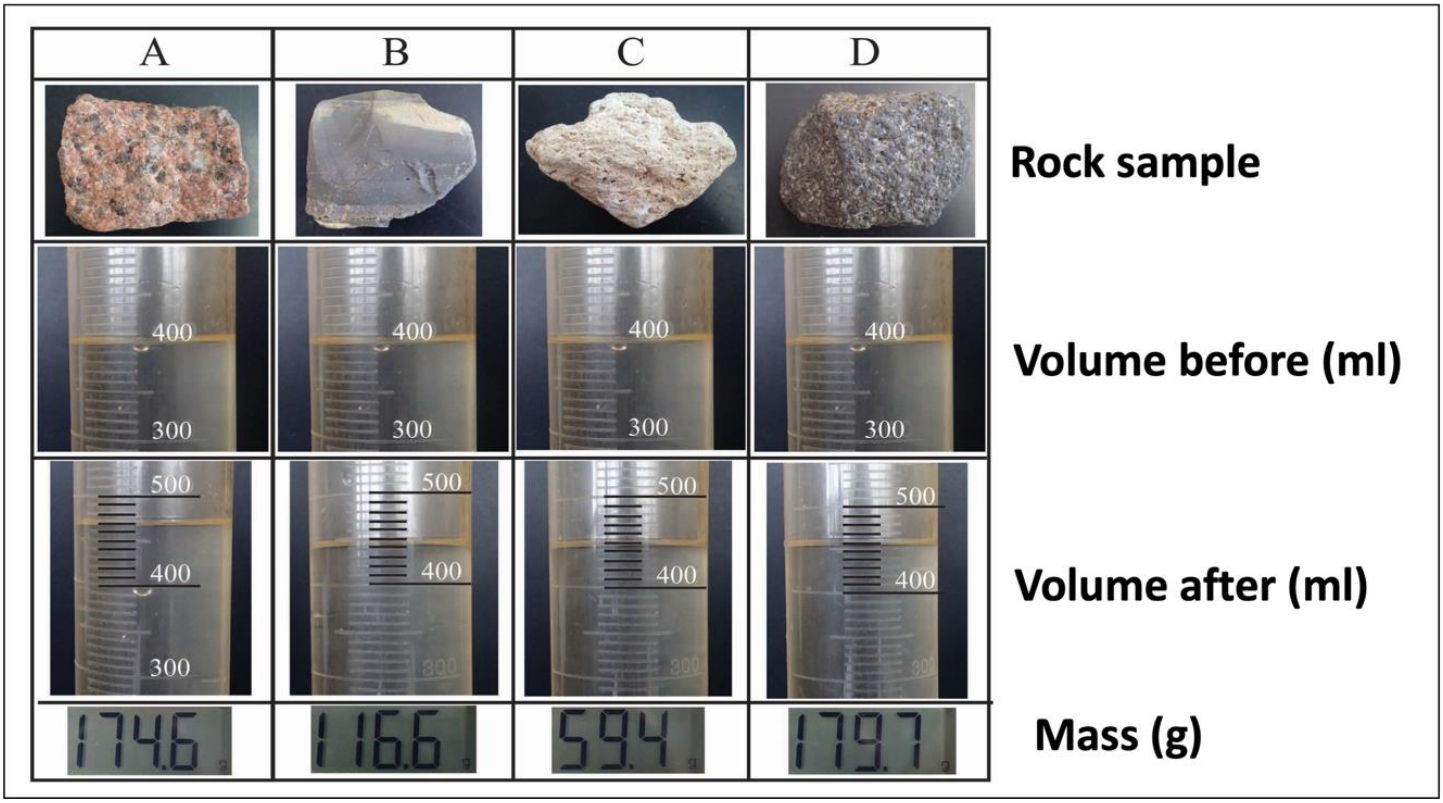


Figure 5.13: Density Experiment: Calculated volumes (in ml) and masses (in g) of rock samples A, B, C, and D.

4. The rock that most closely resembles the composition of continental crust is:

- **a.** A
- **b.** B
- **c.** C
- **d.** D

5. Based on your selection above, what is the density of this rock? *Note: Density = Mass/Volume. Answer unit should be in grams/milliliter.* SHOW YOUR WORK.

6. The rock that most closely resembles the composition of oceanic crust is:

- **a.** A
- **b.** B
- **c.** C
- **d.** D

7. Based on your selection above, what is the density of this rock? *Note: Density = Mass/Volume. Answer unit should be in grams/milliliter.* SHOW YOUR WORK.

8. Based on their densities, when oceanic and continental crust collide, the ??? crust would sink below the ??? crust.

- **a.** continental; oceanic
- **b.** oceanic; continental

9. What type of boundary is represented in the question above?

- **a.** Convergent, subduction
- **b.** Convergent, C-C
- **c.** Divergent
- **d.** Transform

Attributions

- Figure 5.13: Derivative of “Density Experiment” (CC-BY-SA 3.0; Bradley Deline via LibreText) by Chloe Branciforte

Activity 5D: Concept Sketches and Plate Boundaries

A **concept sketch** is a simplified drawing illustrating the main aspects of landscape or system. It is annotated with concise but complete labels that identify important features. Short sentences describe the processes that are occurring. The final aim is to show the relationships between features and processes. It is not simply a sketch labeled with only the names of features. See a rubric below for what is expected for each success level. Point values will be determined by your instructor.

Skill	Emerging	Progressing	Partial Mastery	Mastery
Identify **Features**	Incomplete labeling.	Some labeling.	Most clearly labeled.	Relevant features clearly labeled.
Identify **Processes**	Incomplete identification and description.	Incomplete identification or description.	Clear identification and description.	Relevant processes clearly identified and described.
Explain **the Connections and Relationships Between Features/Processes**	Incomplete connections/relationships.	Suggests some connections/relationship.	Most connections/relationships highlighted effectively.	Relevant connections/relationships highlighted effectively.
Demonstrate **Proper Use of Terminology**	Incomplete or inappropriate use of terminology/units. Frequent errors and misunderstanding of the subject.	Attempts use of appropriate terminology/units. Some errors and missing components.	Consistent use of appropriate terminology/units. Few errors or missing components.	Consistent and successful use of appropriate terminology/units.
Assess **Scientific Accuracy**	Lacks organization with frequent errors, demonstrating misunderstanding of the subject.	Drawings are readable, with occasional oversimplifications, errors and/or missing components.	Drawings are readable. Consistent use of symbology and/or colors/patterns to illustrate major features and/or processes.	Drawings are clearly readable with accurate details illustrated through appropriate symbols and/or colors/patterns. Sketch shows a scale.

Table 5.3: Rubric for geology concept sketches.

More on Concept Maps is available via NAGT/SERC, Teach the Earth.

1. Draw a concept sketch of a **mid-ocean ridge**. Labels should be short sentences explaining the relationships between geologic features and processes.

2. Draw a concept sketch of a **subduction zone**. Labels should be short sentences explaining the relationships between geologic features and processes.

Attributions

- Table 5.3: “Concept Sketch Rubric” (CC-BY 4.0; Chloe Branciforte and Emily Haddad, own work)

Activity 5E: Plate Boundaries

Earthquakes are great indicators of plate boundaries and are associated with all three boundary types.

1. The **Wadati-Benioff zone** is associated with which type of plate boundary?
    - **a.** Divergent
    - **b.** Convergent collision zone (Continent-Continent)
    - **c.** Convergent subduction zone (Continent-Ocean or Ocean-Ocean)
    - **d.** Transform

2. Download the front portion of the The Dynamic Planet map from the USGS. Which of the following locations represent a Wadati-Benioff zone?
    - **a.** 10°S, 110°W
    - **b.** 0°, 0°
    - **c.** 15°S, 180°
    - **d.** 30°N, 75°E

3. Open the browser version of Google Earth and type 34°46'16.2"N 118°44'58.2"W into the search bar. Zoom out to an eye altitude (camera) of 10 miles. This is Quail Lake, a dammed river that sits directly on top of the San Andreas Fault (SAF). The SAF is a well-known transform boundary with the North American Plate on the northern side and the Pacific Plate on the southern side. This boundary is running East-West in this area (dashed line in **Figure 5.14**). Zoom out more in Google Earth and you should be able to see it better.

4. Examine the path of the waterway that feeds into and flows out of Quail Lake. What direction is the North American plate moving in comparison to the Pacific Plate at this location? Draw arrows indicating the motions on **Figure 5.14**.
    - **a.** East
    - **b.** West

5. Given that San Francisco is located on the North American Plate and Los Angeles is located on the Pacific Plate, are these two cities getting closer together or farther apart over time?
    - **a.** Closer
    - **b.** Farther

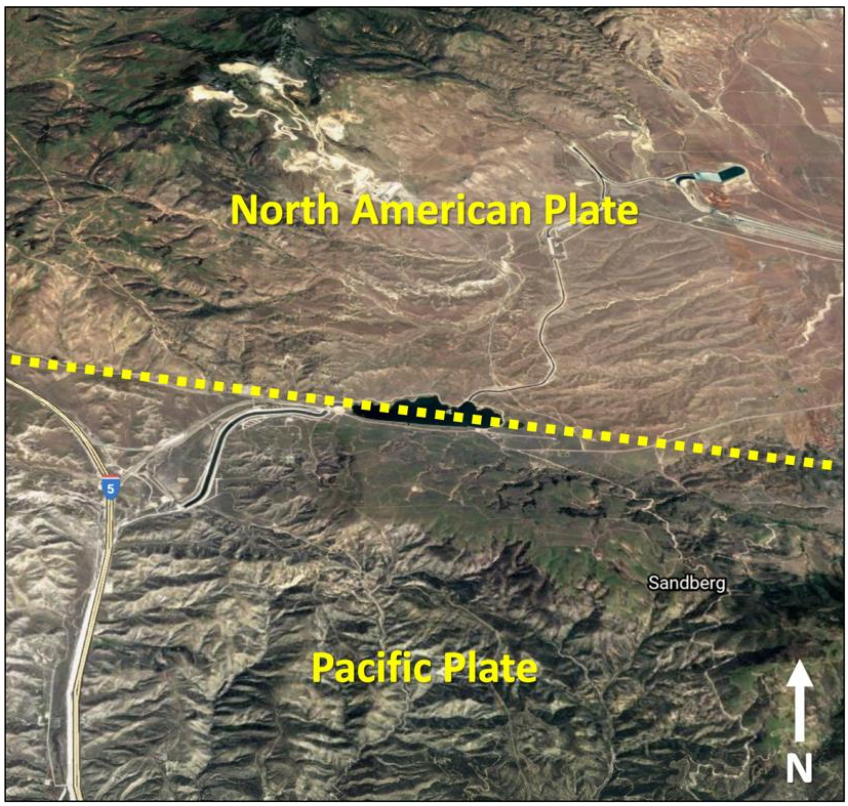


Figure 5.14: Map view of the North American and Pacific Plates.

6. Type 41°47'22.68"N, 124°15'0.51"W into the Google Earth Search bar. What type of tectonic plates are present?
    a. Ocean-Ocean
    b. Ocean-Continent
    c. Continent-Continent

7. What type of plate tectonic boundary is present?
    a. Transform
    b. Convergent, subduction zone
    c. Convergent, collision zone (continent-continent)
    d. Divergent

8. What features would you expect to occur at this type of boundary?
    a. Volcanos, earthquakes and a trench
    b. Volcanoes and a linear valley
    c. Mountains and landslides
    d. Earthquakes and offset rivers

9. Type 23°26’04”N, 108°29’25”W into the Google Earth Search bar. What type of process is going on at this location?
    a. Seafloor spreading
    b. Continental rifting
    c. Subduction

10. What features would you expect to occur at this type of boundary?
    a. Earthquakes and a trench
    b. Submarine volcanic activity and earthquakes
    c. Mountains and landslides
    d. Earthquakes and offset rivers

11. Type 27°58'42.06"N, 86°55'11.53"E into the Google Earth Search bar. What type of tectonic plates are present?
    a. Ocean-Ocean
    b. Ocean-Continent
    c. Continent-Continent

12. What type of plate tectonic boundary is present?
    a. Transform
    b. Convergent, subduction zone
    c. Convergent, collision zone
    d. Divergent

13. Type 43°29'9.14"N, 128° 7'27.37"W into the Google Earth Search bar. This is known as the Blanco Fracture Zone. What type of tectonic plates are present?
    a. Ocean-Ocean
    b. Ocean-Continent
    c. Continent-Continent

14. What type of plate tectonic boundary does the Blanco Fracture Zone represent?
    a. Transform
    b. Convergent, subduction zone
    c. Convergent, collision zone
    d. Divergent

15. This plate boundary isn't as simple as the previous examples, meaning another nearby plate boundary directly influences it. Zoom out and examine the area, what other type of boundary is nearby?

- **a.** Divergent, continental rift
- **b.** Convergent, subduction zone
- **c.** Convergent, collision zone
- **d.** Divergent, mid-ocean ridge

Attributions

- Figure 5.2: “Fault” (CC-BY 4.0; Chloe Branciforte using Google Earth, own work)

Chapter 6: Earthquakes

Learning Outcomes

After completing this chapter, you should be able to:

- ✓ Determine how to locate the epicenter of an earthquake.
- ✓ Determine liquefaction vulnerability of a community.
- ✓ Identify how different geologic materials behave during an earthquake, and the resulting impact on structures.
- ✓ Identify earthquake hazard potential of the Bay Area.

Thumbnail for Chapter 6:

Thumbnail: "Surface Rupture" (Public Domain; USGS)

What Is An Earthquake?

An **earthquake** is a sudden shaking of the ground primarily as a result of fault movement. However, volcanic activity, landslides, impacts, or even human-induced activity can trigger an earthquake. Earthquakes have been experienced by humans throughout our short history. Most ancient cultures developed myths to explain them, including envisioning large creatures - gods or goddesses - within Earth moving to create the quake.

On July 5, 2019, a 7.1 magnitude earthquake hit Ridgecrest, California. This was the **main shock** of the sequence; the previous day, a 6.4 magnitude **foreshock** (smaller earthquakes that precede the main earthquake) occurred. Both earthquakes were felt over a wide area of Southern California. Thousands of **aftershocks** (smaller earthquakes that follow a larger earthquake) have occurred since (**Figure 6.1**).

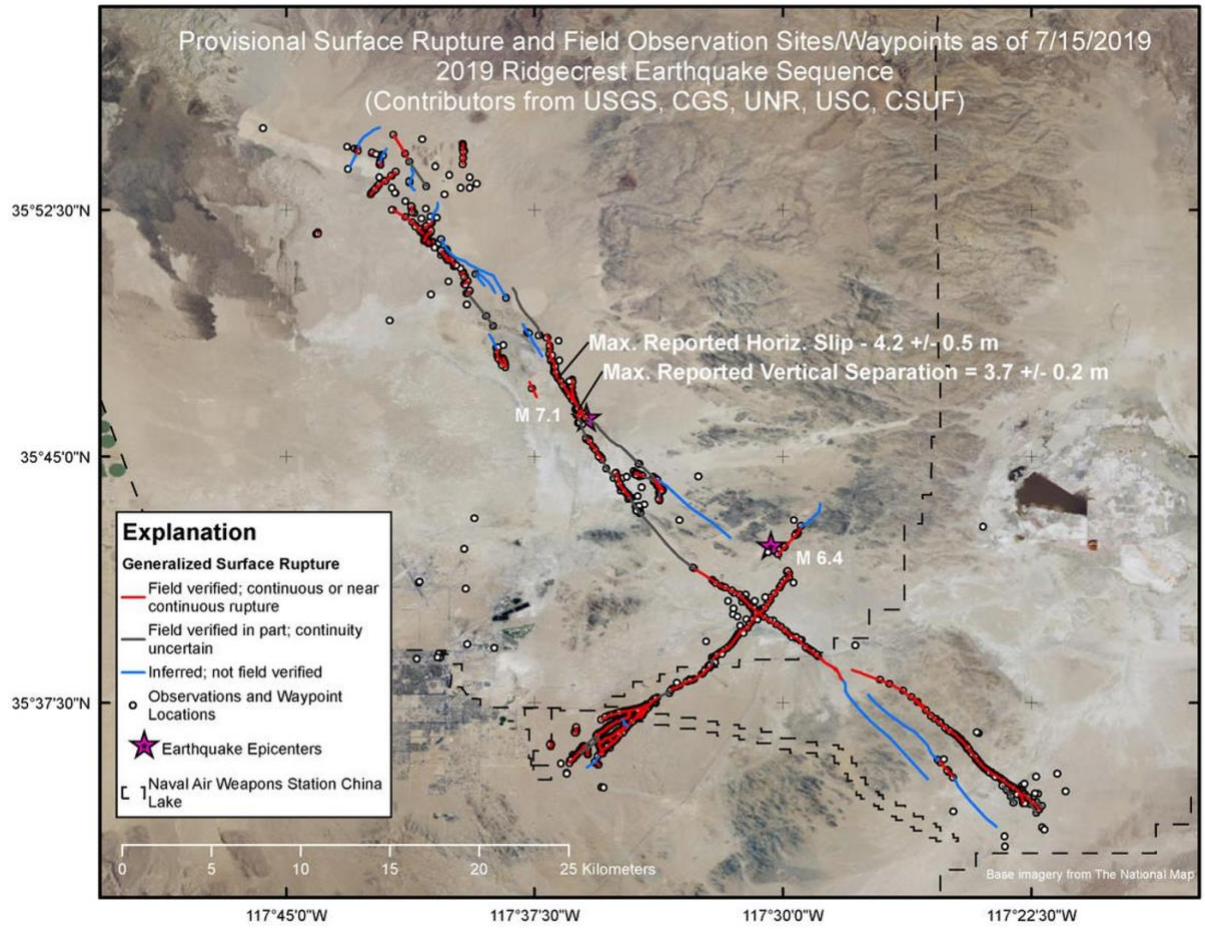


Figure 6.1: General surface rupture based on field mapping and satellite data as of July 15, 2019. Ruptures from the magnitude 6.4 event trend northeast to southwest, and ruptures from the magnitude 7.1 event trend northwest to southeast. Circles indicate where scientists have visited the fault surface.

California is no stranger to earthquakes. We have many faults and fault systems throughout the state, including the infamous San Andreas Fault. Many of our faults are a consequence of California's position on a tectonic plate boundary. Most earthquakes (95%) occur along plate boundaries, while the remaining 5% occur in the interior of a tectonic plate (intraplate). In North America, most earthquakes occur along the West Coast in association with plate boundaries, but intraplate earthquakes occasionally occur in places like the New Madrid, Missouri area (**Figure 6.2**).

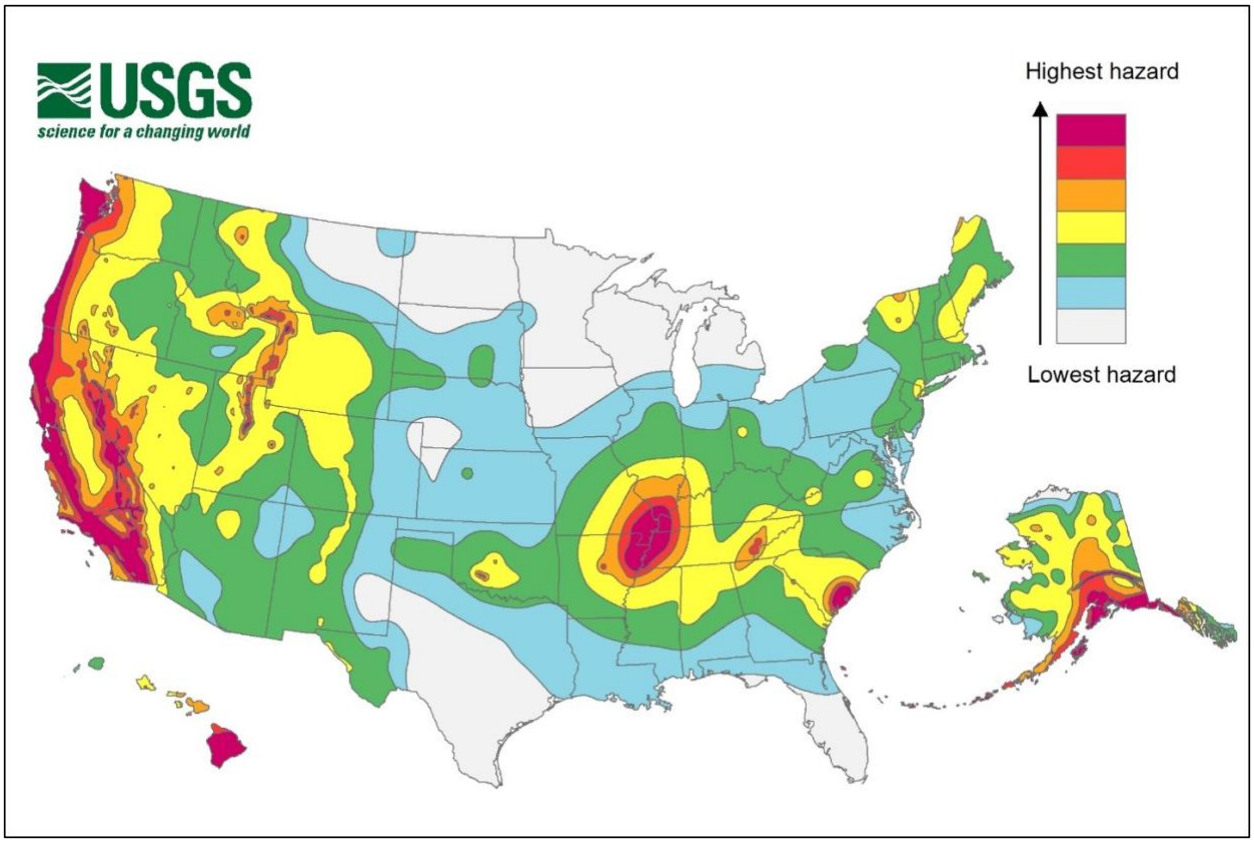


Figure 6.2: Earthquake hazard map showing peak ground accelerations having a 2 percent probability of being exceeded in 50 years, for a firm rock site. The map is based on the most recent USGS models for the conterminous U.S. (2018), Hawaii (1998), and Alaska (2007). The models are based on seismicity and fault-slip rates and consider the frequency of earthquakes of various magnitudes. Locally, the hazard may be greater than shown, because site geology map amplify ground motions.

Earthquakes provide valuable information about conditions in Earth's interior and at the surface. And, unlike previous topics we've explored, earthquakes are a **hazard** with inherent risks to human society. Those of us in California likely have experienced at least one earthquake in our lifetime (maybe more!). Therefore, we are aware of the need to consider hazard mitigation, including planning, preparation, and communication, all commonly supported by the science of **seismology**.

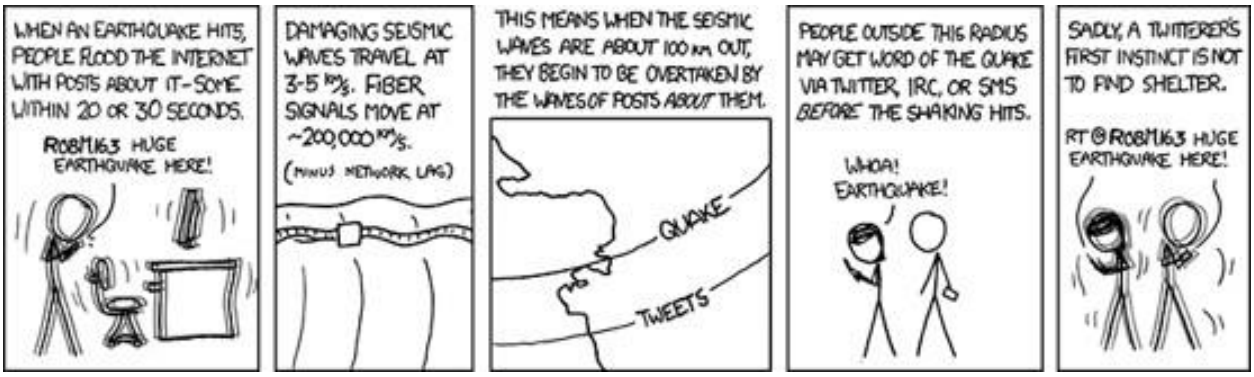


Figure 6.3

Seismologists and geophysicists are the primary investigators of earthquakes; however, other geoscientists may study them, as well. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including in mining and natural resource extraction or in hazard mitigation and assessment. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 6.1: “2019 Ridgecrest Earthquake” (Public Domain; USGS)
- Figure 6.2: “Earthquake Hazard Map” (Public Domain; USGS)
- Figure 6.3: “Seismic Waves” (CC-BY-NC 2.5; xkcd via xkcd.com)

Earthquake Focus, Epicenter, and Waves

Earthquakes originate at a point called the **focus** (plural *foci*) or hypocenter. From this point, energy travels outward in different types of waves. The place on the Earth's surface directly above the focus is called the **epicenter** (**Figure 6.4**). Earthquake foci may be shallow (less than 45 miles from Earth's surface) to deep (greater than 185 miles deep), though shallow to intermediate depths are much more common. Earthquake frequency and depth are related to plate boundaries. The vast majority (95%) of earthquakes occur along a plate boundary, with shallow focus earthquakes tending to occur at divergent and transform plate boundaries, and shallow, intermediate, and deep focus earthquakes occurring at convergent boundaries (along the subducting plate). The earthquakes associated with convergent boundaries occur along **Wadati-Benioff zones**, or simply Benioff zones, areas of dipping seismicity along the subducting plate (**Figure 6.5**).

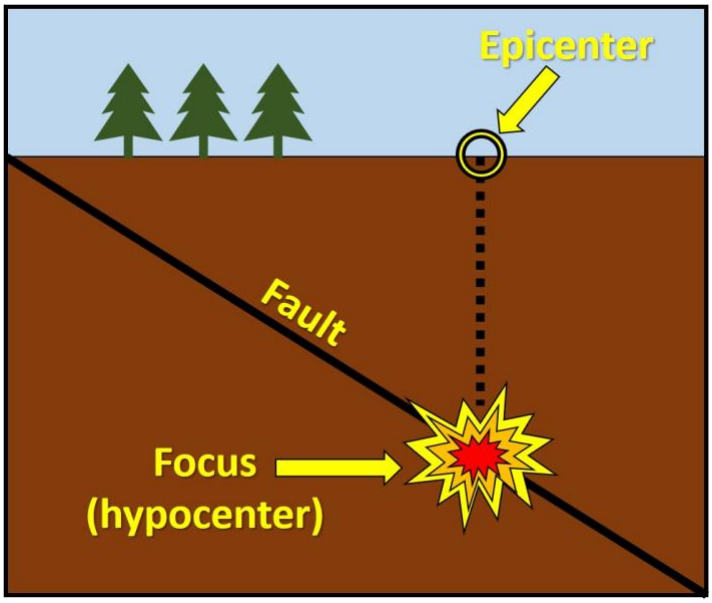


Figure 6.4: An illustration depicting the focus, where the earthquake originates, and the epicenter, the point on the ground's surface directly above the focus.

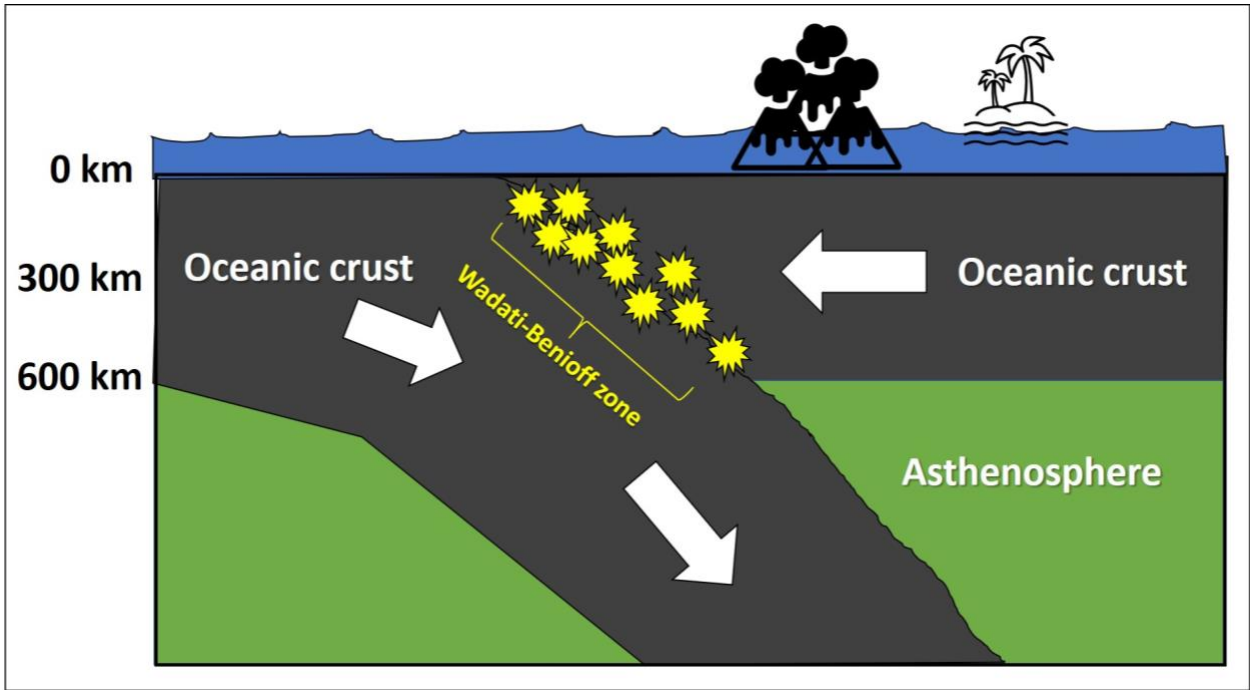


Figure 6.5: An illustration depicting a subduction zone with associated Wadati-Benioff Zone.

Attributions

- Figure 6.4: “Earthquake Focus and Epicenter” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 6.5: “Wadati-Benioff Zone” (CC-BY 4.0; Chloe Branciforte, own work)

Earthquake Waves

As an earthquake occurs, two different types of waves are produced: 1) **body waves**, so termed because they travel through the body of the Earth, and 2) **surface waves** that travel along the Earth's surface. There are two types of body waves: P-waves and S-waves. **P-waves**, or **primary waves**, are compressional waves that move back and forth, like the action of an accordion. As the wave passes, the atoms in the material it is travelling through are compressed and stretched (**Figure 6.6**). Movement is compressional parallel to the direction of wave propagation, which makes P-waves the fastest of the seismic waves. These waves can travel through solids, liquids, and gases, because all materials can be compressed to some degree.

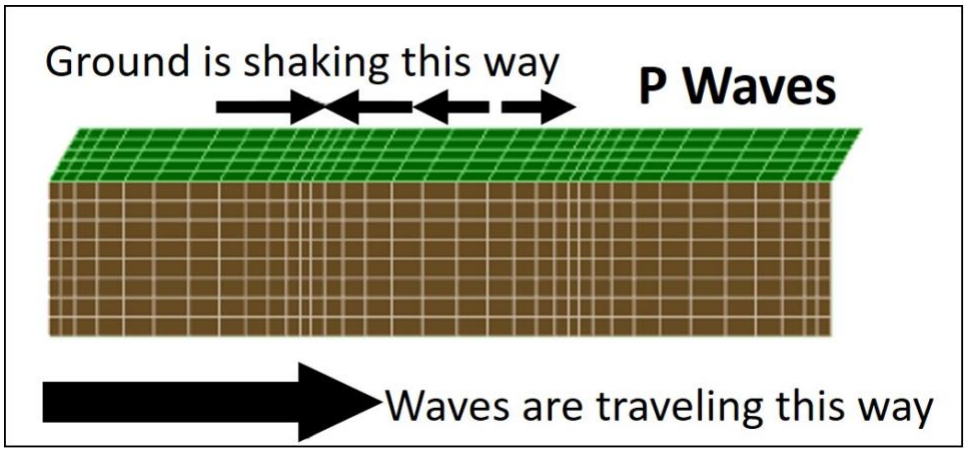


Figure 6.6: P-wave and their general movement through a rock body.

S-waves, or **secondary waves**, are shear waves that move material in a direction perpendicular to the direction of travel (**Figure 6.7**). S-waves can only travel through solids and are slightly slower than P-waves. Think of a wave movement like the wave created by fans in a stadium that stand up and sit down. Body waves are often responsible for the jerking and shaking motions felt during an earthquake.

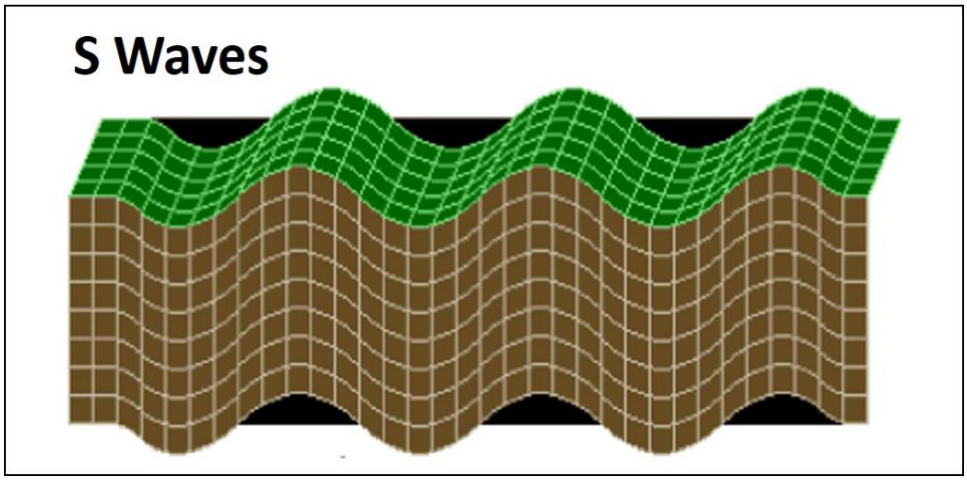


Figure 6.7: S-wave and their movement through a rock body.

Surface waves, which are only propagated along the surface of the Earth, are slower than body waves. Additionally, their movement is often not handled by buildings well, so these waves are responsible for considerable damage to structures. These waves move slowly, which often results in an increase in amplitude. **Love waves** are the faster surface waves, and they move material back and forth in a horizontal plane that is perpendicular to the direction of wave travel (**Figure 6.8**). **Rayleigh waves** make the Earth's surface move in an elliptical, rolling motion, like the movement in an ocean wave (**Figure 6.8**). Combined, this results in ground movement that is both up and down and side-to-side.

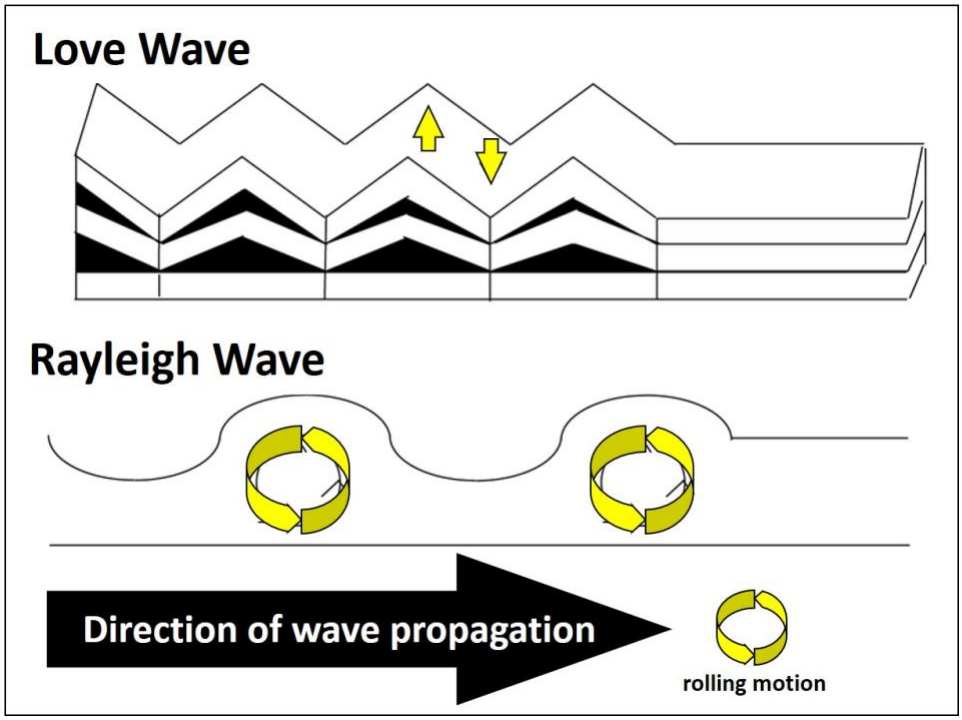


Figure 6.8: Love and Rayleigh wave propagation.

Category	Type	Velocity (miles per second)	Arrival placement at distant seismogram
Body	Primary (P)	5 mi/s	First
Body	Secondary (S)	3 mi/s	Second
Surface	Love (L)	2.8 mi/s	Third
Surface	Rayleigh (R)	2.2 mi/s	Fourth

Table 6.1: Summary table of the different seismic waves and their arrival order to a distance seismic station.

Want to view seismic waves in action? Visit the **Incorporated Research Institutions for Seismology (IRIS)** for videos showing wave motion.

Attributions

- Figure 6.6: Derivative of “P wave” (Public Domain; USGS)
- Figure 6.7: Derivative of “S wave” (Public Domain; USGS)
- Figure 6.8: Derivative of “Surface Wave Motion” (CC-BY 3.0; Jcrane81 via Wikimedia Commons) by Chloe Branciforte
- Table 6.1: “Seismic Waves” (CC-BY 4.0; Chloe Branciforte, own work)

Recording Earthquakes

The formal study of earthquakes, called **seismology**, began with the development of instruments that were capable of detecting earthquakes. This instrument, called a **seismograph or seismometer**, can measure the slightest of Earth's vibrations (**Figure 6.9**). A typical seismograph consists of a mass suspended on a string from a frame that moves as the Earth's surface moves. A rotating drum is attached to the frame, and a pen attached to the mass, so that the relative motion is recorded in a **seismogram** (**Figure 6.10**). It is the seismograph frame, attached to the ground, that moves during an earthquake. The suspended mass generally stays still due to **inertia**.

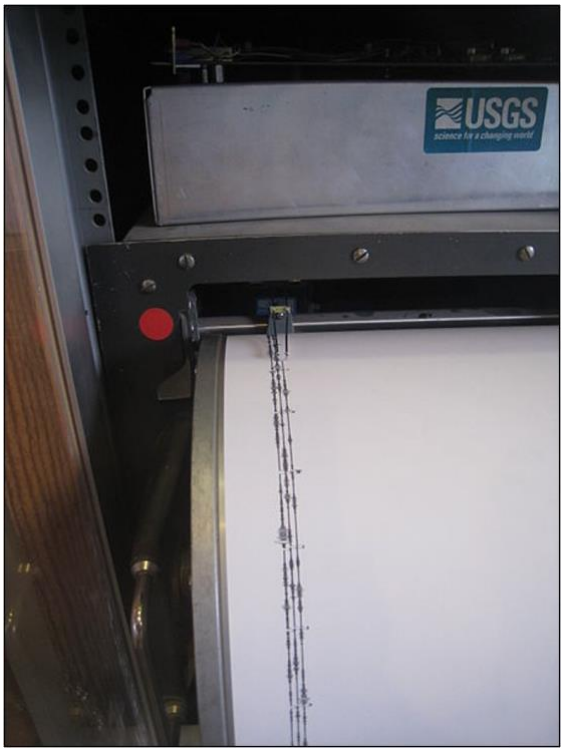


Figure 6.9: A USGS seismograph at the Point Reyes visitor center, near the San Andreas Fault.

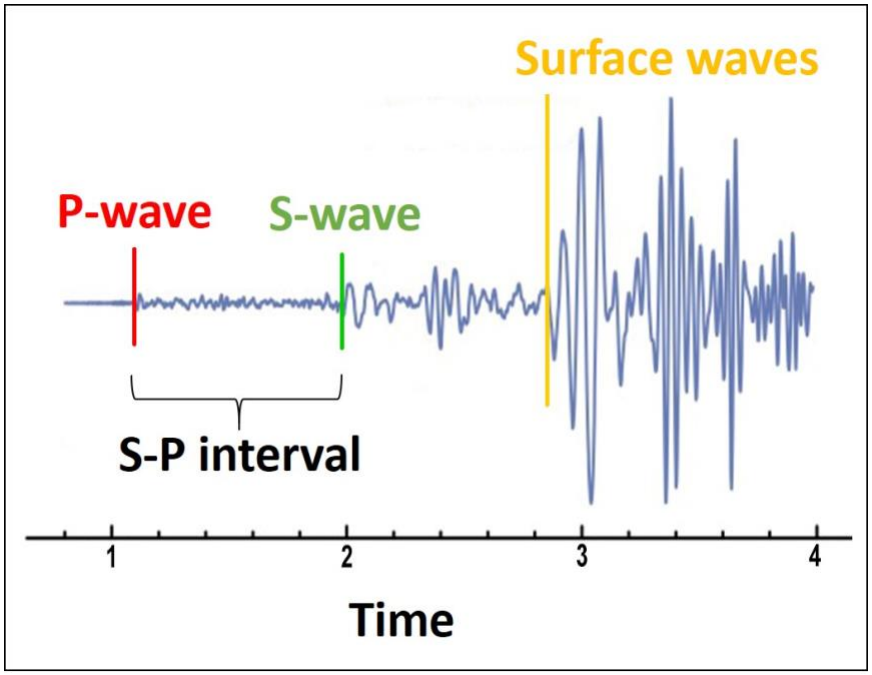


Figure 6.10: The P-waves are the first to arrive at each station, followed by the S-waves. Because the P-waves travel faster than S-waves the great distance between the two (S-P interval), the further away the earthquake epicenter.

Attributions

- Figure 6.9: “USGS Seismograph Point Reyes” (CC-BY-SA 3.0; Dvortygirl via Wikimedia Commons)
- Figure 6.10: Derivative of “S-P Interval Seismogram Distance to Earthquake” (CC-BY-SA 4.0; Benjamin J. Burger via Wikimedia Commons)

How Are Earthquakes Measured?

The tragic consequences of earthquakes can be measured in many ways, like death tolls or force of ground shaking. However, there are two measures that are commonly used. One is a qualitative measure of the damage inflicted by the earthquake, referred to as **intensity**. The second is a quantitative measure of the energy released by the earthquake, termed **magnitude**. Both measures provide meaningful data.

Earthquake Intensity

Intensity measurements consider both the damage incurred due to the quake and the way that people respond to it. The **Modified Mercalli Intensity Scale** (**Table 6.2**) is the most widely used scale to measure earthquake intensities. This scale has values that range from Roman numerals I to XII that characterize the damage observed and people's reactions to the shaking.

Modified Mercalli Intensity Scale	
Intensity	**Characteristics**
I	Shaking is not felt under normal circumstances.
II	Shaking felt only by those at rest, mostly along upper floors in buildings.
III	Weak shaking felt noticeably by people indoors. Many do not recognize this as an earthquake. Vibrations like a large vehicle passing by.
IV	Light shaking felt indoors by many, outside by few. At night, some were awakened. Dishes, doors, and windows disturbed; walls cracked. Sensation like a heavy truck hitting a building. Cars rock noticeably.
V	Moderate shaking felt by most; many awakened. Some dishes and windows are broken. Unstable objects overturned.
VI	Strong shaking felt by all, with many frightened. Heavy furniture may move, and plaster breaks. Damage is slight.
VII	Very strong shaking sends all outdoors. Well-designed buildings sustain minimal damage; slight-moderate damage in ordinary buildings; considerable damage in poorly built structures.
VIII	Severe shaking. Well-designed buildings sustain slight damage; considerable damage in ordinary buildings; great damage in poorly built structures.
IX	Violent shaking. Well-designed buildings sustain considerable damage; buildings are shifted off foundations, with some partial collapse. Underground pipes are broken.
X	Extreme shaking. Some well-built wooden structures are destroyed; most masonry and frame structures are destroyed. Landslides considerable.
XI	Few structures are left standing. Bridges are destroyed, and large cracks open in the ground.
XII	Total damage. Objects thrown upward in the air.

Table 6.2: The Modified Mercalli Intensity scale, roman numeral rankings and their associated characteristics.

Data for the Mercalli scale is often collected right after an earthquake by having the local population answer questions about the damage they see and what happened during the quake. This information can then be pooled to create an intensity map, which creates colored zones based on the information collected (**Figure 6.11**). These maps are frequently used by the insurance industry. Should you ever experience an earthquake, once safe, consider reporting your experience to the United States Geological Survey (USGS) via their **"Did You Feel It?"** tool. You can help geoscientists examine the earthquake impacts in your region.

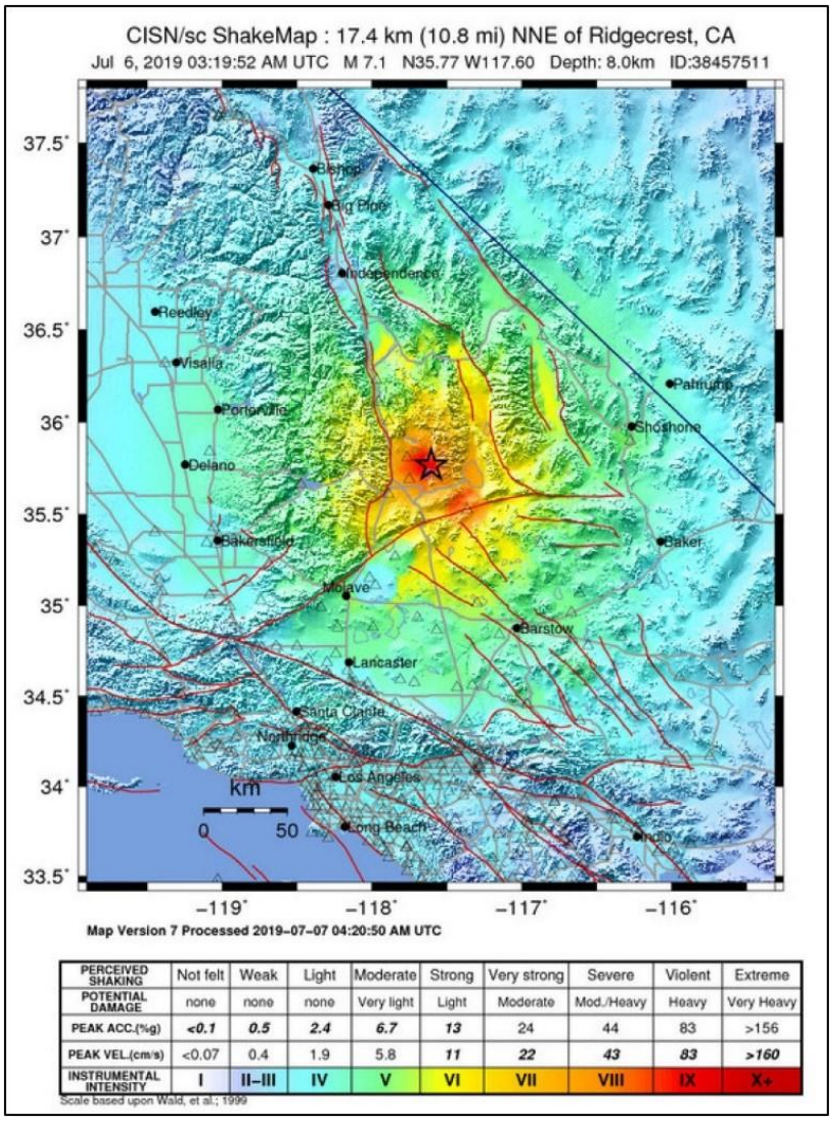


Figure 6.11: The ShakeMap for the magnitude 7.1 Ridgecrest earthquake (July 6, 2019) shows shaking in the region varied from weak to violent.

Earthquake Magnitude

Another way to classify an earthquake is by the energy released during the event; this is referred to as the magnitude of the earthquake. Magnitude has been historically measured using the **Richter scale**; however, as the frequency of earthquake measurements around the world increased, seismologists realized the Richter magnitude scale was not valid for all earthquakes, specifically large magnitude earthquakes. A new scale called the **Moment Magnitude Scale** was developed, which maintains a similar logarithmic scale to the Richter scale. This scale estimates the total energy released by an earthquake and can be used to characterize earthquakes of all sizes throughout the world. The magnitude is based on the seismic moment, estimated based on ground motions recorded on a seismogram, which is a product of the distance a fault moved and the force required to move it. This scale works particularly well with larger earthquakes and has been adopted by the USGS.

Magnitude is based on a logarithmic scale, which means for each whole number increased, the

amplitude of the ground motion recorded by a seismograph increases by 10 and the energy released increases by 101.5, rather than one. A magnitude 3 earthquake results in ten times the ground shaking as a magnitude 2 quake; a magnitude 4 quake has 102 or 100 times the level of ground shaking as a magnitude 2 quake, releasing 103 or 1000 times as much energy. For a rough comparison of magnitude scale to intensity (**Table 6.3**).

Magnitude	Qualitative Descriptor	Typical Maximum Modified Mercalli Intensity
1.0 – 2.9	Micro	I– III
3.0 – 3.9	Minor	III - IV
4.0 – 4.9	Light	IV – V
5.0 – 5.9	Moderate	V – VI
6.0 – 6.9	Strong	VI – VII
7.0 -7.9	Major	VIII-VII
8.0 and above	Great	VII or higher

Table 6.3: Relationship between magnitude and intensity values.

Why is it necessary to have more than one type of scale? The magnitude scale allows for worldwide characterization of any earthquake event, while the intensity scale does not. With an intensity scale, an IV in one location could be ranked II or III in another location, based off of building construction. For example, poorly constructed buildings will suffer more damage in the same magnitude earthquake as those built with stronger construction.

Energy comparison: On August 4th, 2020, 2,750 tons of ammonium nitrate ignited and exploded in the Port of Beirut in Lebanon. This explosion damaged most structures within a 3-mile radius and was heard in Cyprus more than 100 miles away. The explosion was devastating; hundreds were killed and thousands injured and many were displaced from their homes. This event was roughly equivalent to a 1-3 kiloton TNT explosion which roughly translates to a M4.5 earthquake. However, seismic stations throughout the region recorded the event as a M3.3. This discrepancy is likely due to the fact that the explosion was at the surface, resulting in most of the energy traveling up into the air and into the surrounding buildings in lieu of traveling through the rock.

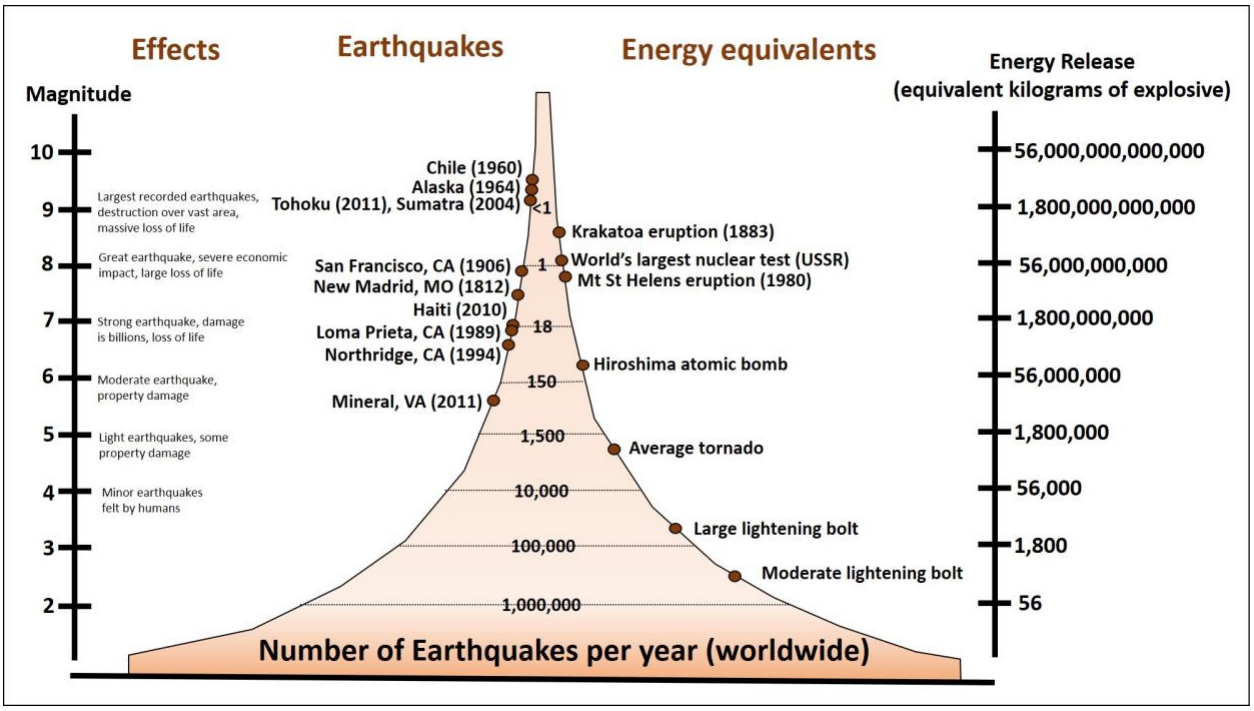


Figure 6.12: Large earthquakes occur about once a year. Smaller earthquakes such as magnitude 2 earthquakes, occur several hundred times a day.

Attributions

- Table 6.2: “Modified Mercalli Intensity Scale” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 6.11: “ShakeMap for 2019 Ridgecrest Earthquake” (Public Domain; USGS)
- Table 6.3: “Magnitude and Intensity” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 6.12: How Often Do Earthquakes Occur? ©IRIS Consortium. Adapted and used with permission (16 November 2020). [All rights reserved].

How Are Earthquakes Located?

During an earthquake, seismic waves are propagated throughout the entire Earth. Though they may weaken with distance, seismographs are sensitive enough to detect these waves. In order to determine the location of an earthquake epicenter, seismographs from at least three different locations are needed. Once three seismographs have been located, the **S-P interval** must be measured (**Figure 6.13**). To do this, you must first determine when the P-wave arrived at the seismograph station. On the seismogram, find the arrival of the P-wave, which can be recognized by an increase in amplitude (wave height), and note the time of P-wave arrival. Repeat this procedure for the S-wave, then subtract the arrival time of the P-wave from the arrival time of the S-wave. In general, longer time S-P intervals indicate further station distance from an epicenter.

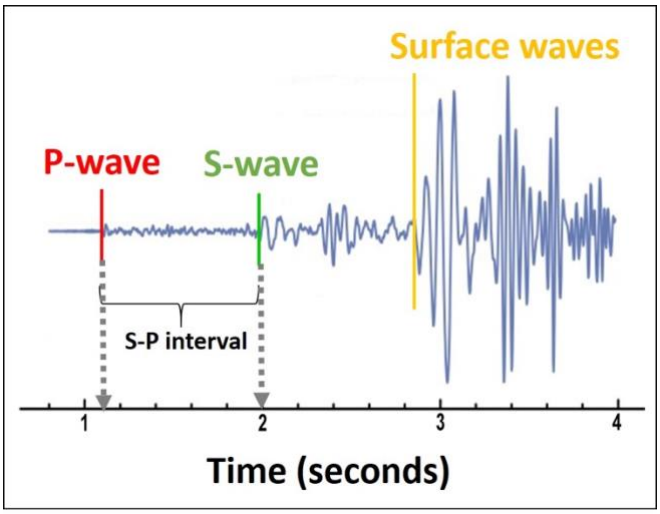


Figure 6.13: The P-waves are the first to arrive at each station, followed by the S-waves. The P-waves travel faster than S-waves the great distance between the two (S-P interval), the further away the earthquake epicenter.

Once you have calculated the S-P interval, you will now be able to determine the distance to an earthquake epicenter from a specific seismic station. This is typically done using a **travel-time curve**, which is a graph of P- and S-wave arrival times (**Figure 6.14**).

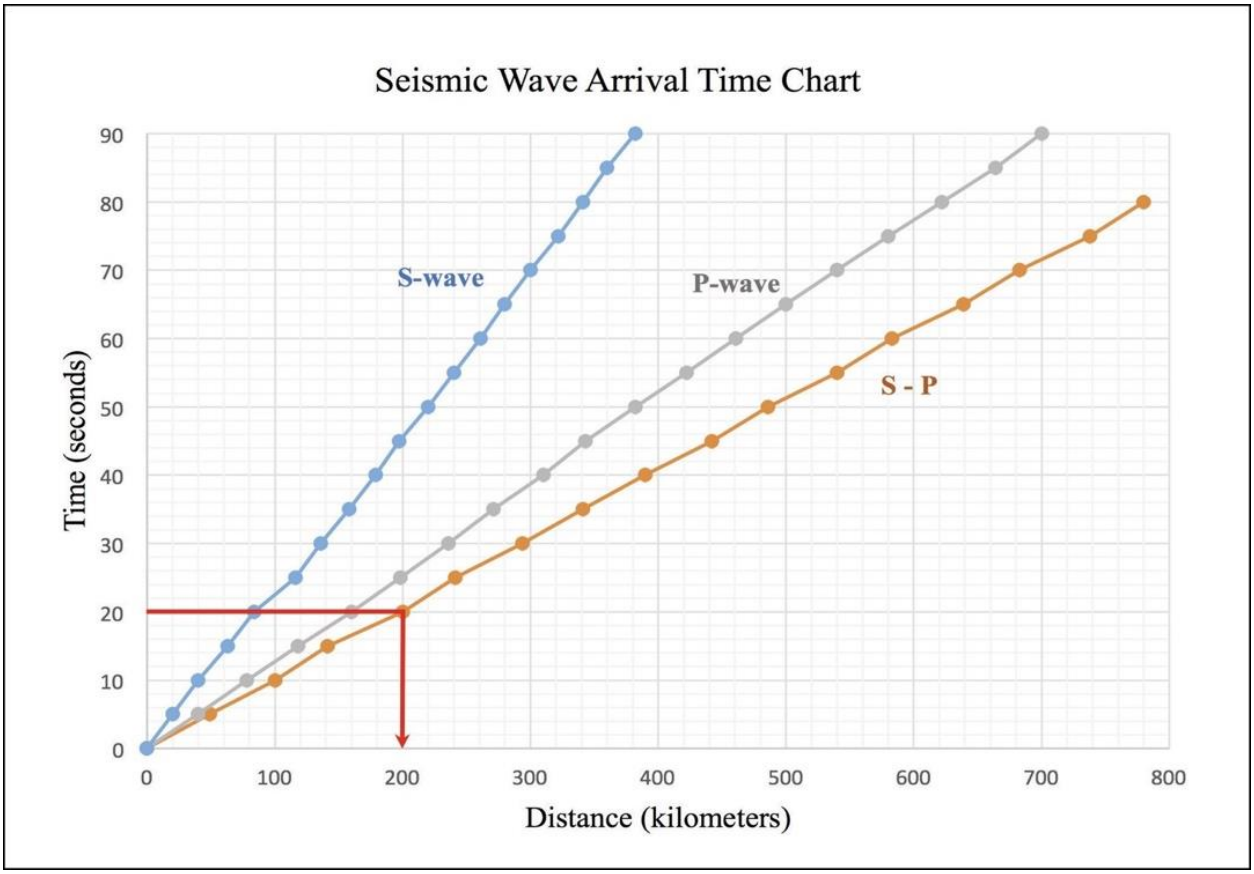


Figure 6.14: A travel-time graph that includes the arrival of P-waves and S-waves. Note that these curves plot distance versus time and are calculated based on the spherical shape of Earth. Curves vary with the depth of earthquake because waves behave differently with depth and change in material. This curve is used for shallow earthquakes (<20 km deep) with stations within 800 km. The S-P curve refers to the difference in time between the arrival of the P-wave and S-wave.

Though *distance* to the epicenter can be determined using a travel-time graph, *direction* cannot. To pinpoint the location of the epicenter, we can use distance information from three seismograph stations and triangulate. To do this, draw a circle around one of the seismograph locations with a radius of the distance to the earthquake. We know that the earthquake occurred somewhere along this circle, but a circle contains an infinite number of possible epicenters; this is why it is necessary to have data from at least three seismic stations. Draw a circle around at least two more seismograph locations, where the radius of each circle is equal to the distance from that station to the epicenter. The spot where those three circles intersect is the epicenter (**Figure 6.15**).

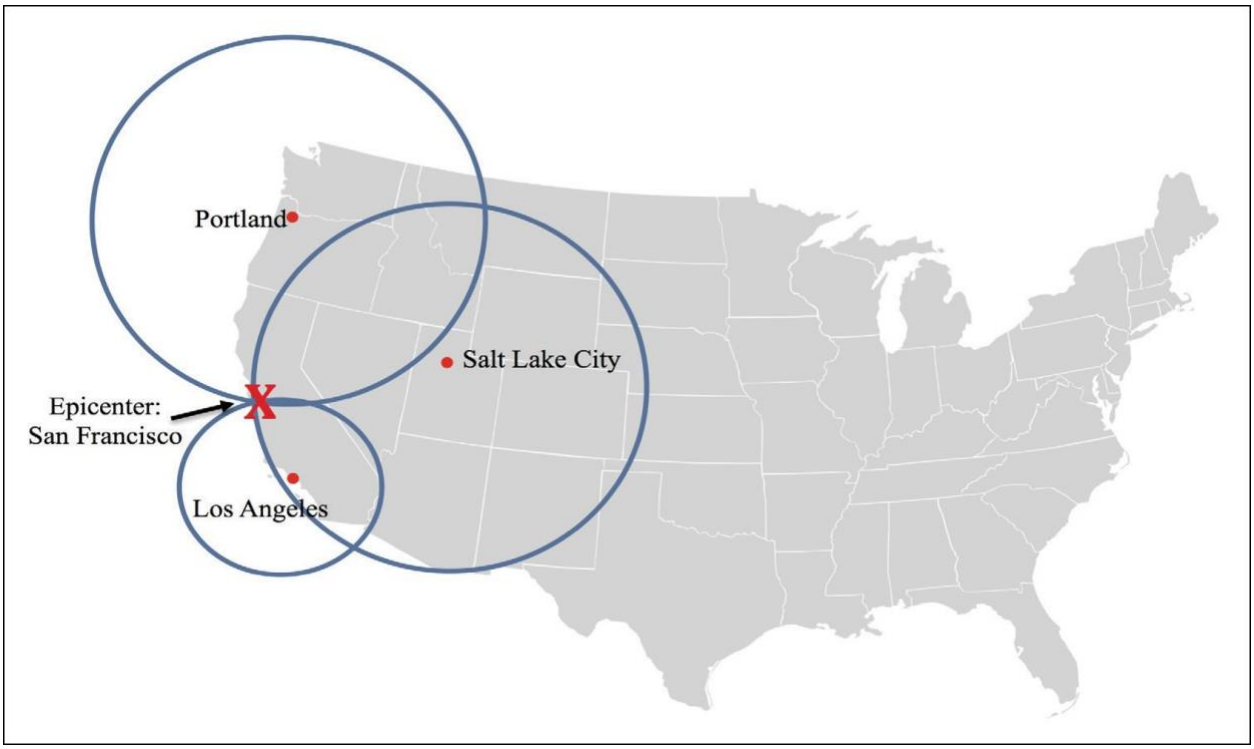


Figure 6.15: In order to locate this earthquake's epicenter, seismograms from Portland, Salt Lake City, and Los Angeles were used. The time between P and S wave arrivals was calculated, and travel timetables gave a distance. Circles with each distance for their radii were drawn from each station. The one resulting overlap, at San Francisco, was the earthquake epicenter.

Attributions

- Figure 6.13: Derivative of “S-P Interval” (CC-BY-SA 4.0; Benjamin J. Burger via Wikimedia Commons) by Chloe Branciforte
- Figure 6.14: “Seismic Wave Arrival Chart” (CC-BY-SA 3.0; Randa Harris, own work via LibreTexts)
- Figure 6.15: “Epicenter Distance” (CC-BY-SA 3.0; Randa Harris, own work via LibreTexts)

Hazards from Earthquakes

Earthquakes are among nature's most destructive phenomena, and there are numerous hazards associated with them. **Ground shaking** can lead to falling structures, making it the most dangerous earthquake-related hazard. The intensity of ground shaking depends on several factors, including the size of the earthquake, the duration of shaking, the distance from the epicenter, and the material the ground is made of. Solid bedrock will not shake much during a quake, rendering it safer than other ground materials. Typically, **seismic waves will amplify** as they encounter weaker geologic materials (sediments), and this amplification can be destructive (**Figure 6.16**).

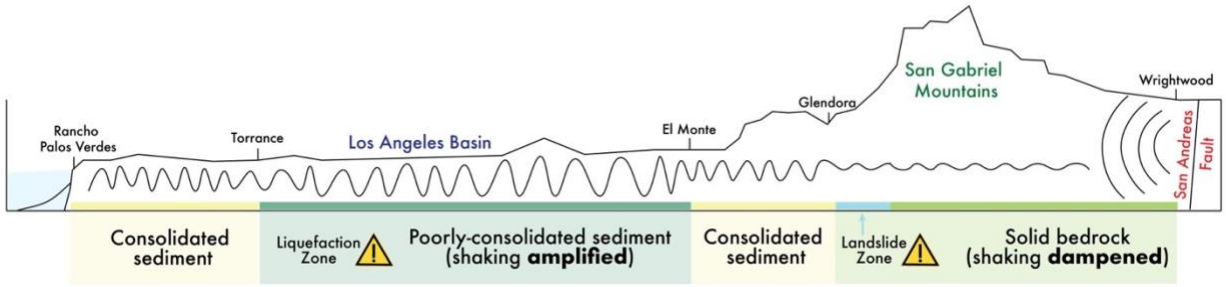


Figure 6.16: Earthquake waves amplify (wave height increases) in poorly consolidated sediments, which can lead to more intense shaking and liquefaction.

In addition to wave amplification, loose, water-saturated sediments or artificial fill can serve as sites for **liquefaction**. Normally, friction between grains holds them together; however, as unconsolidated sediments are shaken, water surrounds every grain, eliminating the friction and allowing them to liquefy (**Figure 6.17**). Liquefaction can cause major damage to buildings and infrastructure, sand and water to be ejected in "**sand volcanoes**", and the ground surface to be permanently deformed. Want to see a fun experiment? Check out this jacuzzi filled with sand!

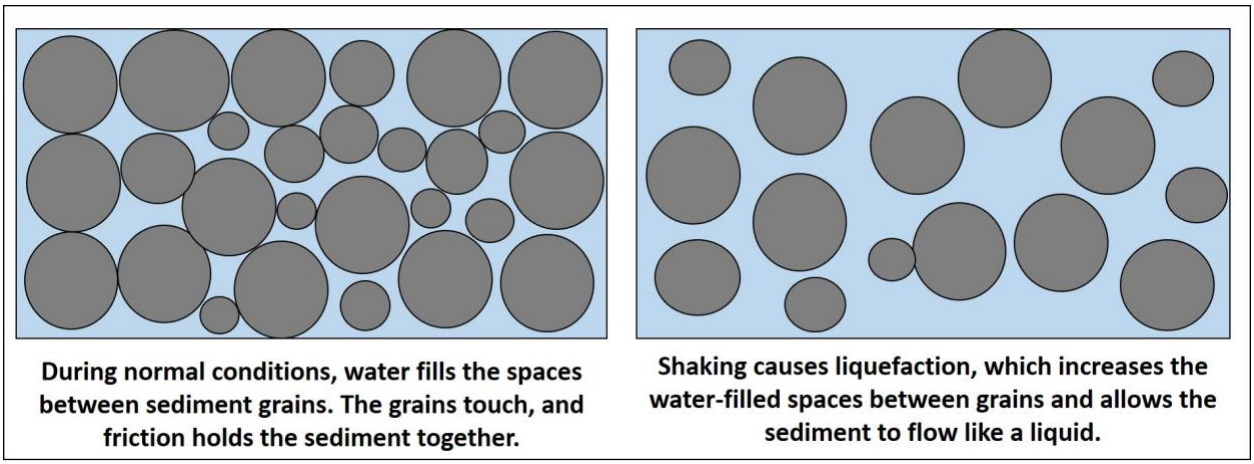


Figure 6.17: *Left:* During normal conditions, water fills the spaces between sediment grains. The grains touch, and friction holds the sediment together. *Right:* Shaking causes liquefaction, which increases the water-filled spaces between grains and allows the sediment to flow like a liquid.

Large (M7.5+) earthquakes typically displace the seafloor, which can trigger **tsunamis**. These large ocean waves are often associated with **subduction zone earthquakes**. The **Sumatra-Andaman earthquake in 2004** triggered a tsunami in the Indian Ocean that resulted in almost 230,000 deaths. In 2011, the **Tohoku earthquake** off the coast of Japan triggered a tsunami wave that heavily impacted the country, killing more than 15,000 and causing the meltdown of the Fukushima Daiichi Nuclear Power Plant.

Figure 6.18: USGS geologists make measurements of fault rupture after the Searles Valley Earthquake, July 2019.

Earthquakes can also 1) ignite fires, like the conflagration experienced following the **Great San Francisco Earthquake** of 1906, 2) result in major ground rupture, like the rupturing experienced during the Ridgecrest earthquakes in 2019 (**Figure 6.18**), and 3) trigger landslides, like. the more than 10,000 landslides experienced in the LA area in the wake of the Northridge earthquake in 1994. Typically, landslides will occur in areas with steep slopes, like the mountains, or underwater. Underwater landslides may also trigger tsunami, and, if coupled with a subduction zone earthquake, may result in a taller-than-predicted wave. Earthquake-prone areas can take steps to minimize destruction, such as implementing strong building codes, early warning systems, addressing poverty and social vulnerability, retrofitting existing buildings, and limiting development in hazardous zones. **Earthquake forecasting** (**Figure 6.19**) can help communities

plan for their future risk. Want to know your hazard potential? Visit the California Department of Conservation's **EQ Zapp: California Earthquake Hazards Zone Application**.

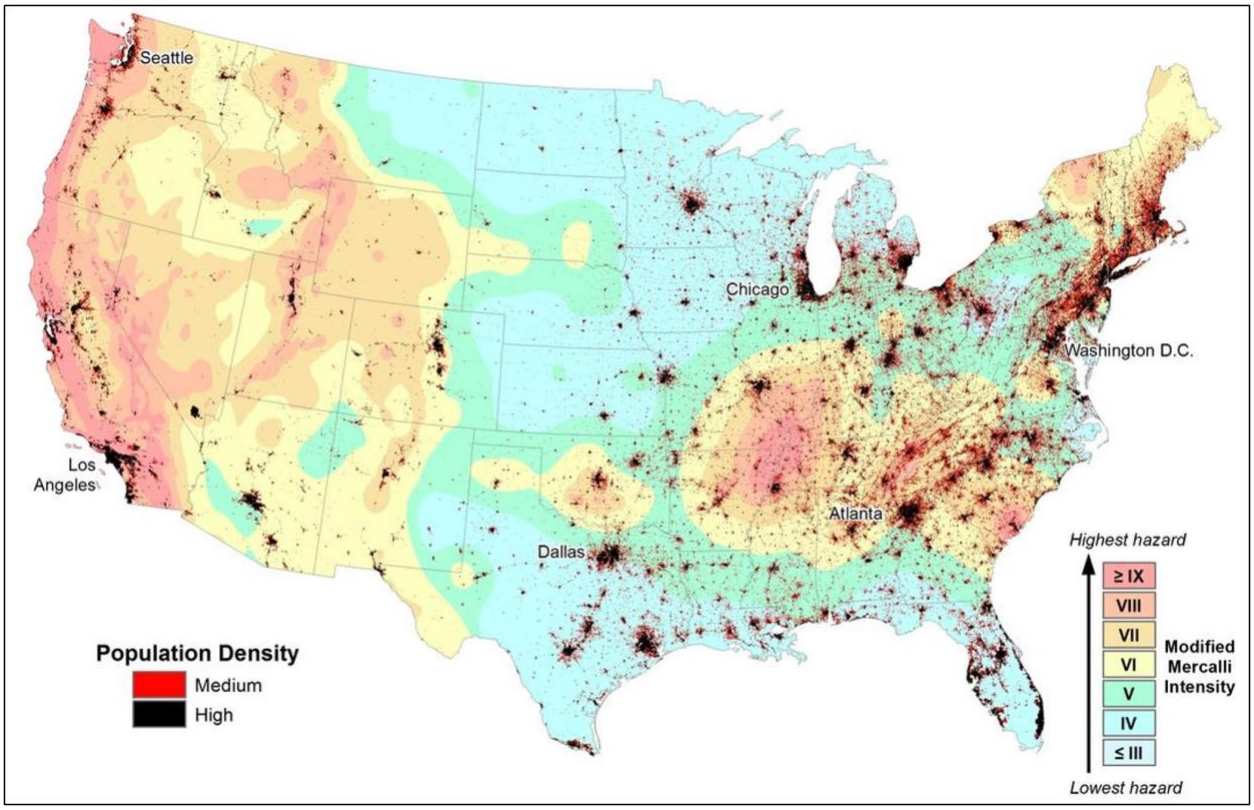


Figure 6.19: USGS map showing (1) the locations of major populations and (2) the intensity of potential earthquake ground shaking that has a 2% chance of occurring in 50 years.

Attributions

- Figure 6.16: “Liquefaction and Amplification in SoCal” (CC-BY 4.0; Emily Haddad, own work)
- Figure 6.17: “Liquefaction” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 6.18: “Surface Rupture” (Public Domain; USGS)
- Figure 6.19: “USGS Earthquake Hazard Map” (Public Domain; USGS)

Induced Seismicity

In some intraplate areas of the country, like Oklahoma, earthquake numbers in a single year can exceed even what we experience here in California. The majority of these earthquakes are a result of human activity and are known as **induced seismicity**. Humans have induced earthquakes in the past, but the increasing frequency of episodes of induced seismicity has led to more dedicated research into the problem. Evidence points to several contributing factors, all related to types of fluid injection used by the oil industry. **Hydraulic fracturing**, also referred to as **fracking**, has been used for decades by oil and gas companies to improve well production. Fluids, usually water, are injected at high pressure into low-permeability rocks to fracture the rock. As more fractures open within the rock, fluid flow is enhanced and more distant fluids can be accessed, increasing the production of a well. In the past, this practice was utilized in vertical wells. However, with the recent advent of horizontal drilling technology, the fracking industry has really taken off. Drillers can now access thin horizontal oil and gas reservoirs over long distances, greatly increasing well production in rocks that formerly were not exploited, driving a boom in US natural gas and oil production.

While there have been many reports in the media that blame the process of hydraulic fracturing for all the increased seismicity rates, this is not the full story. Fracking mainly produces very minor earthquakes, less than magnitude 3 (although it has been shown to produce significant earthquakes on occasion). Instead, the majority of induced earthquakes are actually caused by the injection of wastewater deep underground. Wastewater injection is a byproduct of fracking, so ultimately the industry is to blame. As wells are developed (by fracking or other processes), large amounts of waste fluid, which typically contain potentially hazardous proprietary chemicals, are created. When the fluids cannot be recycled or stored in retention ponds above ground, they are injected deep underground, theoretically deep enough to not encounter oil reservoirs or water supplies. These wastewater wells are quite common and are considered a safe option for wastewater disposal. By injecting this water in areas that contain faults, however, the stress conditions on the faults change as friction is reduced, which can result in movement along faults and earthquakes.

In 2005, the White Wolf fault located southeast of Bakersfield (**Figure 6.20**), experienced an earthquake swarm. Peak activity occurred on September 22, 2005 with multiple quakes ranging from M4.3-4.6. Nearby is the Tejon Oil field, which between 2001 and 2010 increased the rate of wastewater injection by over 26.4 million gallons of water each month. Ultimately, this put pressure on the White Wolf fault, which then ruptured, producing the swarm. Want to learn more about fracking? Visit the USGS Myths and Misconceptions About Induced Earthquakes.

Figure 6.20: White Wolf Fault shown in yellow with the San Andreas Fault in orange.

Attributions

- Figure 6.19: “White Wolf Fault” (CC-BY 4.0, Chloe Branciforte via Google Earth, own work)

Activity 6A: Locating an Epicenter

1. Navigate to the Virtual Earthquake website.

2. Complete the Virtual Earthquake program for each of the four listed earthquake examples.

    a. San Francisco area
    b. Southern California
    c. Japan region
    d. Mexico

3. To earn credit, be sure to check with your instructor to see how they want you to submit proof of completion. The program will provide you with a certificate of completion, which you can then download and email directly to your instructor, submit online through your LMS (Canvas, Moodle, etc), or print and hand in during your next lab meeting.

Activity 6B: Liquefaction

Launch the EQ Zapp: California Earthquake Hazards Zone. Turn off all layers except for liquefaction.

1. What color is used to signify a liquefaction zone on this map?

2. A significant earthquake hits while you are visiting friends in San Mateo, California. During the shaking you find yourself caught indoors. Where would you rather be caught indoors?

    a. US Social Security Administration Building (800 S Claremont Street, San Mateo)

or

    b. San Mateo Park Rangers (1901 J Hart Clinton Drive, San Mateo)

Why?

3. The opportunity to move to the Bay Area of California arises, and you are planning to live in the Oakland/Alameda region. After learning about earthquakes in your physical geology class, you want to ensure you are prepared for the inevitable. Part of your preparation is to consider the location of your future home, school, and hospital. To ensure you are ready for the inevitable earthquake, you prepare by learning where important services and places are located. You also consider the risks of these places/locations. In the event you or someone in your family needs to visit the hospital, which one would you prefer to visit?

    a. Highland Hospital (1411 E 31st Street, Oakland)

or

    b. Alameda Hospital (2070 Clinton Ave, Alameda)

Why?

4. Check with your instructor for another location. They may ask you to enter your home or school address in the search bar. Is this new location in a designated liquefaction zone?

    a. Yes
    b. No

Activity 6C: Earthquakes and Faults in California

1. Navigate to the California Geological Survey's Fault Activity Map of California.

2. Check with your instructor for a location. They may ask you to enter your home or school address in the search bar.

3. How close is the nearest fault to you? *Note: there is a scale bar in the lower left-hand corner of the map.*

4. What geologic age is this fault? *Note: locate the* *at the top of the map to open the symbol explanation.*

    a. Holocene
    b. Late Quaternary
    c. Quaternary
    d. Pre-Quaternary

5. Navigate to the California Geological Survey's ShakeMap Home Page. Identify the most recent event. What is the

    a. Location?

    b. Date?

    c. Magnitude?

6. Select the most recent significant event. What is the

    a. Highest intensity value on the map?

    b. Color associated with this value?

Activity 6D: Earthquakes and the Bay Area

The following exercises use Google Earth. Start by examining the USGS site for the 1906 earthquake that hit Northern California. There are several links available on this page. Spend some time familiarizing yourself with the site.

Scroll down to the section entitled "The Northern California Earthquake, April 18, 1906" and open the link. The San Andreas Fault, located here in California, is approximately 800 miles long. In 1906, a major earthquake occurred along a northern portion of the fault.

1. Scroll down and check out the **Rupture Length and Slip**. How long was the rupture length (the length of the fault that was affected)?

    a. 25 miles
    b. 74 miles
    c. 198 miles
    d. 296 miles
    e. 408 miles

2. Horizontal slip, or relative movement along the fault, ranged from 2-32 feet. Check out all the measurements along the fault by clicking the Rupture Length and Slip, Google Earth file at the bottom of the section. Locate the epicenter of the 1906 quake (about 2 miles west of San Francisco). Does the amount of horizontal slip decrease faster along the northern end or the southern end of the rupture?

    a. Northern end of the rupture
    b. Southern end of the rupture

Go back to the "The Northern California Earthquake, April 18, 1906" page and scroll down to **Shaking Intensity**. Check out the intensity values by clicking the Shaking Intensity, Google Earth file at the bottom of the section. *Note - if your map begins to get difficult to read, remember that by clicking on a checkbox in the Places folder, you can remove prior data. Use the search box to display the desired location.*

3. What was the shaking intensity like in Sacramento?
    a. Light
    b. Strong
    c. Severe
    d. Violent
    e. Extreme

4. What was the shaking intensity like in Sebastopol?

    a. Light
    b. Strong
    c. Severe
    d. Violent
    e. Extreme

5. Navigate to the "Earthquake Hazards of the Bay Area Today". Download the Earthquake Probabilities for the Bay Area, Google Earth file. Examine the map carefully. The USGS has calculated the probability of an M≥6.7 earthquake in the Bay Area between 2003-2031. In which part of the Bay Area is the probability highest?

    a. Northwest Bay Area
    b. Southeast Bay Area

6. Go back to the "Earthquake Hazards of the Bay Area Today" page and download the Liquefaction Susceptibility in San Francisco, Google Earth file. Observe the overall trend in areas affected by liquefaction. Based on this map, are areas more susceptible to liquefaction inland or along the coast?

    a. Inland
    b. Along the coast

Appendix: California Earthquake Resources

- California Integrated Seismic Network
- Northern California Earthquake Data Center
- Southern California Earthquake Data Center
- Significant Faults and earthquakes in SoCal
- USGS Earthquake Hazards - Global Monitoring

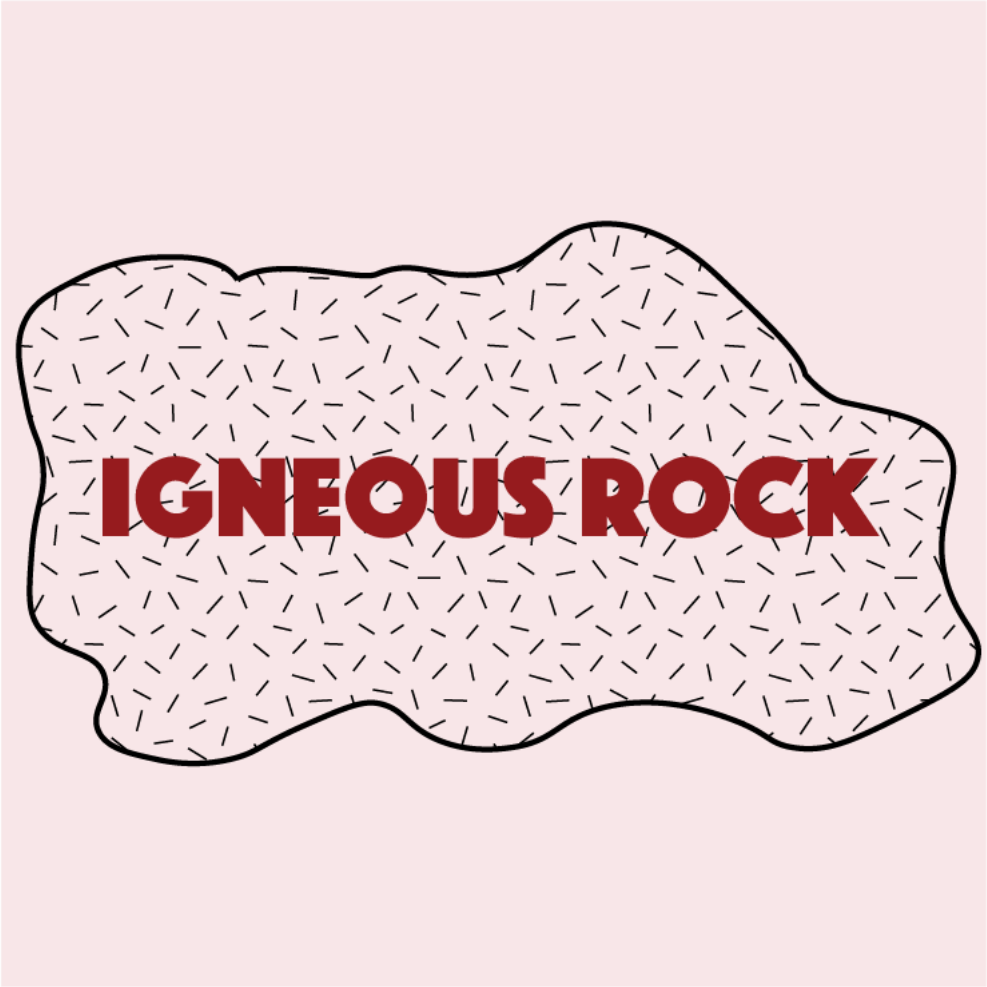
Chapter 7: Igneous Rocks and Processes

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Determine the cooling history of the igneous rock.
- ✔ Identify, when possible, the minerals present in an igneous rock.
- ✔ Classify igneous rock types based on color, composition, and texture.

Thumbnail for Chapter 7:



Thumbnail: "Igneous Rock" (CC-BY 4.0; Emily Haddad, own work)

What Is the Rock Cycle?

The rock cycle is a circular diagram that demonstrates the process by which rocks are continually recycled throughout geologic time. All rocks can be classified into one of three groups: igneous, sedimentary, or metamorphic. This rock classification is based on the origin of each of these rock types, or the processes that form the rock. **The Rock Cycle** (**Figure 7.1**), represents the processes that produce each of the rock types. **Igneous rocks** are produced through the melting of rock and eventual cooling of lava or magma. As cooling occurs, crystals may form. **Sedimentary rocks** are produced via the processes of weathering (the chemical and physical breakdown of material at Earth's surface that produces sediments), erosion (the movement and deposition of sediments), and lithification (the compaction and cementation of sediments). **Metamorphic rocks** are produced via the agents of change, primarily heat and pressure, which typically result in the recrystallization of minerals. These processes will be explored in greater detail in each of their respective chapters.

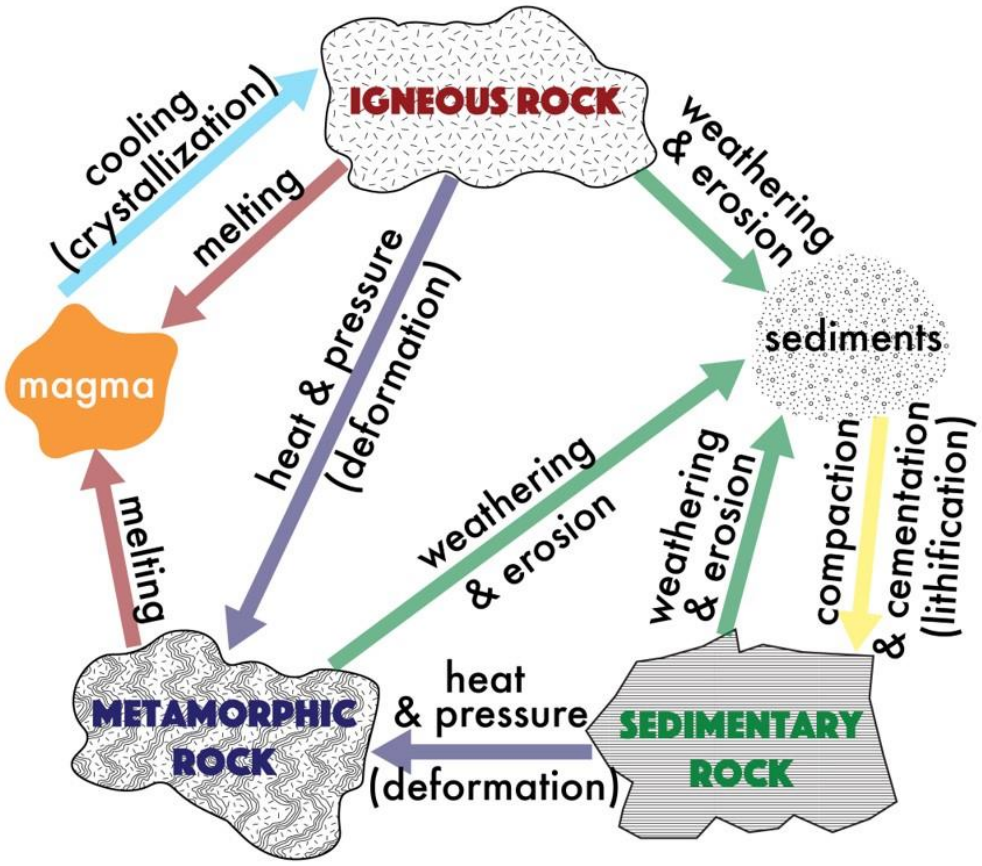


Figure 7.1: The processes of the rock cycle.

Attributions

- Figure 7.1: “The Rock Cycle” (CC-BY 4.0; Emily Haddad, own work)

Igneous Rocks

Igneous rocks are the only rocks that form from a liquid (or molten) state. All igneous rocks start out as molten material (**magma** or **lava**), which must harden to form a rock. Igneous rocks differ from one another primarily due to: 1) the *composition* of the molten material from which the rock is derived, and 2) the *cooling process* of the molten material that formed the rock. These two parameters define the classification of igneous rocks, which are simplified into the two terms: *composition* and *texture*. Igneous rock composition refers to what is in the rock (the chemical composition or the minerals that are present), and the word texture refers to the features that we see in the rock, such as the mineral sizes or the presence of glass, fragmented material, or vesicles (holes) in the igneous rock.

A person who studies igneous rocks is referred to as an igneous petrologist. A petrologist is a geoscientist that studies rocks and the conditions under which they form. An igneous petrologist is a geoscientist who specializes in igneous rocks and their conditions of formation. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and at state and federal agencies, including geological surveys, like the California Geological Survey or United States Geological Survey (USGS). Additional career pathways are available in the private sector including mining and natural resource extraction. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Melting

What Is a Melt?

A "melt" refers to molten rock, typically formed at high temperatures (~2000°F/1090°C). Melts are characterized by where they are located. **Lava** exists at or very near the surface of the Earth, whereas **magma** forms at depth within the crust and **lithosphere**. Although the term "melt" indicates a rock that is completely molten (i.e. a liquid), most melts actually contain all three states of matter. The liquid component is the actual molten rock. The solid components are minerals that have crystallized or glasses that have formed. Lastly, the gaseous components are dissolved within the melt, like carbon dioxide, water vapor, and others. These gases will be an important driver in volcanic eruptions.

Where Do Melts Form?

There are a number of myths surrounding melts. The first often perpetuated myth is that melts come from the outer core. *This is FALSE*. A melt can only originate in the mantle or lithosphere. The second often perpetuated myth is that melts exist everywhere beneath the crust. *This is also FALSE*. Melts only form in specific tectonic settings, including continental volcanic arcs and volcanic island arcs (subduction zones), hot spots, and divergent boundaries (mid-ocean ridges and rifts).

How Do Rocks Melt?

Melting is an interplay between temperature and pressure. Under normal or low pressures, like on the surface of the Earth, you need only 1) add heat, 2) meet or exceed the melting temperature of the object you are trying to melt, and 3) a melt will be produced. For example, chocolate has a relatively low melting temperature, around 90°F, while our body temperature is around 98°F; this is why chocolate will melt in your hand (*and* in your mouth!). Earth's "body" temperature runs much hotter, and temperatures increase with depth moving towards the core; however, pressure also increases with depth. Increasing pressure counteracts increasing temperature, preventing the breaking of mineral bonds and disruption of crystal lattices that are required to melt rocks. In **Figure 7.2**, the red lines represent the **geothermal gradient,** which tracks how temperature increases with depth; the gray areas on the charts represent the temperature and pressure conditions under which rock remains solid, whereas the pink regions represent the temperature and pressure conditions under which rock will melt into liquid. Notice how Earth is not molten throughout; instead melts typically only exist within the crust and upper lithosphere, usually fewer than 50 miles (80 km) from the surface, and form only in

unique tectonic settings where specific conditions are met (i.e. where the geothermal gradient crosses the solidus curve).

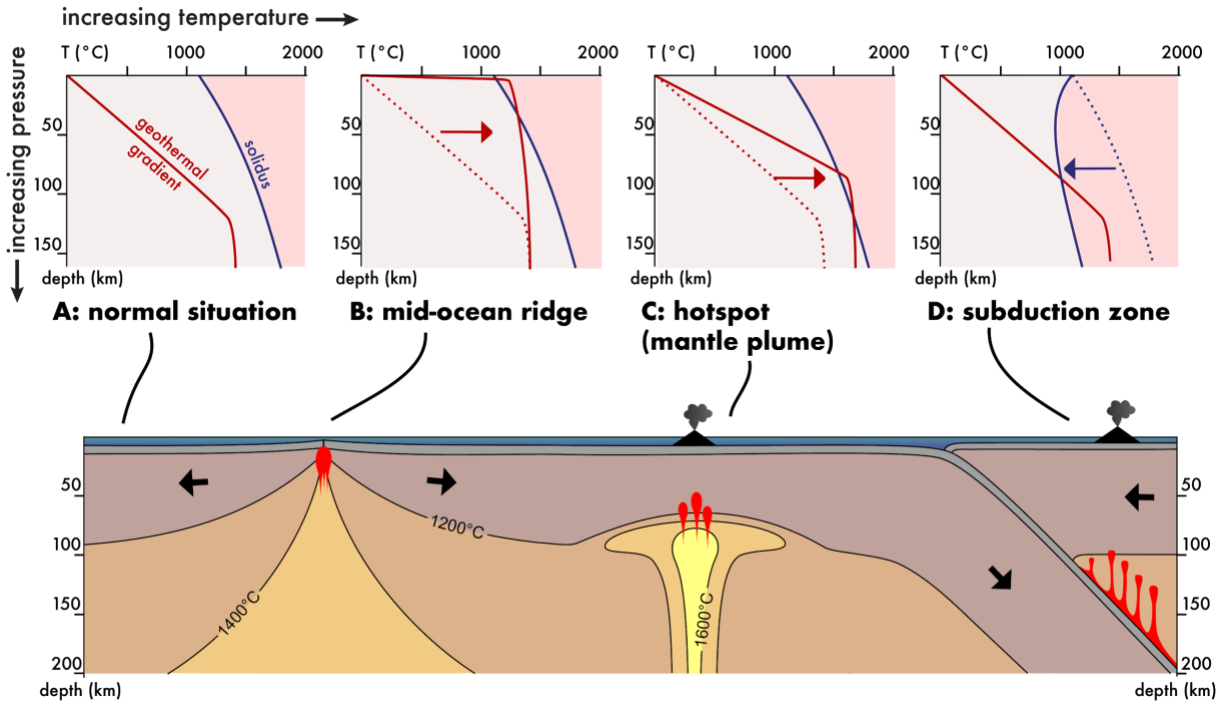


Figure 7.2: Schematic diagram illustrating the physical processes within Earth's upper mantle that lead to the generation of magma. Each graph shows the geothermal gradient (red) and the solidus (blue). When the two curves cross each other, magma is generated by partial melting. A) the curves do not cross; rock does not melt; B) at mid-ocean ridges, rock undergoes decompression melting; C) at a hotspot (mantle plume), rock undergoes decompression melting; D) at a subduction zone, volatiles are added and rock undergoes flux melting.

One way to surpass the melting temperature of a rock and create a melt is through a process called **decompression melting** (**Figure 7.3**). This process relieves pressures on the rock, which shifts the geothermal gradient. Decompression melting occurs at divergent boundaries (MORs and rifts) and hot spots (like Hawaii) (**Figure 7.2B and C**). Here, rock is decompressed at a constant temperature. Convection brings hot mantle from depth and moves it towards the surface. The mantle material stays hotter than the surrounding rocks and, as pressure is relieved, melt is produced. This is why basalt commonly forms at MORs and at hot spots below oceanic plates.

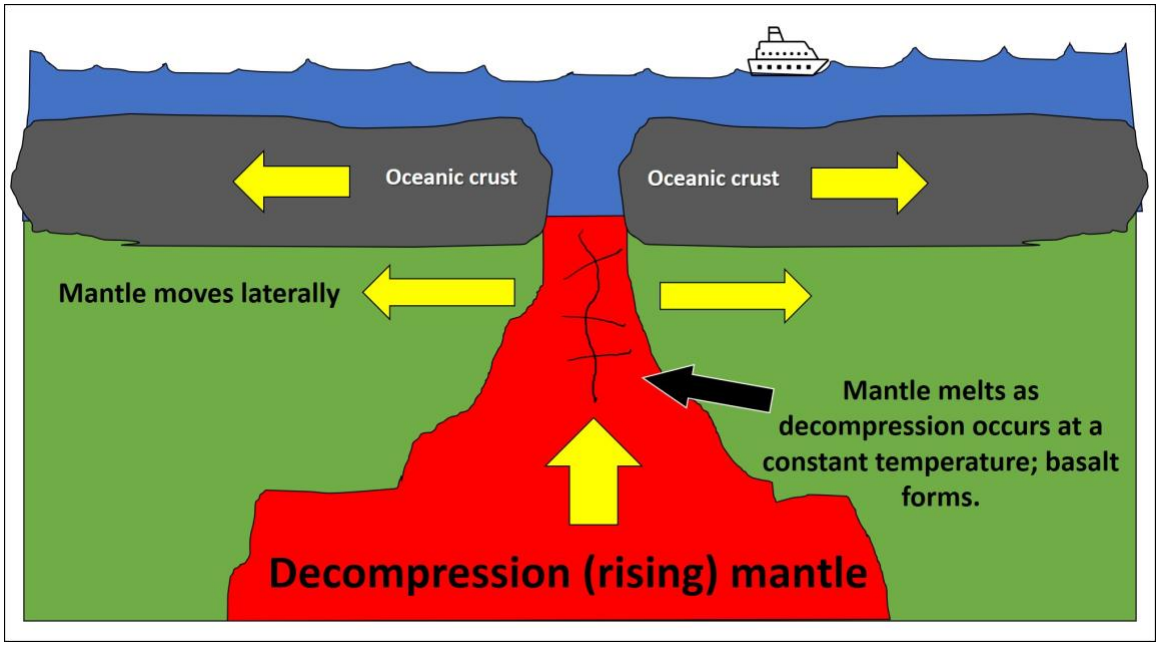


Figure 7.3: An illustration depicting decompression melting in the asthenosphere at mid-ocean ridges (MORs).

Earth has additional processes at play, which help to *lower the melting temperature* of rock. Typically, this occurs through the **addition of volatiles**, in a process called **flux melting** (**Figure 7.4**). At subduction zones, hydrated minerals in the oceanic crust release water as they subduct and heat up. This addition of water into the mantle rock causes the mantle to melt at a lower temperature than its normal melting temperature (**Figure 7.2D**). This process is similar to the use of salt on roadways during the winter months; the salt causes the ice to melt at a lower temperature and helps reduce ice development on roadways. For rock in subduction zones, water behaves like the salt.

Rock can also melt through **conduction**, a simple way to transfer heat. Melt produced through decompression or flux melting is buoyant and will begin to rise toward Earth's surface. As the rising melt interacts with lithospheric rock, it may transfer enough heat to the surrounding rock to melt it. This is why volcanic arcs (both continental and island) form at subduction zones.

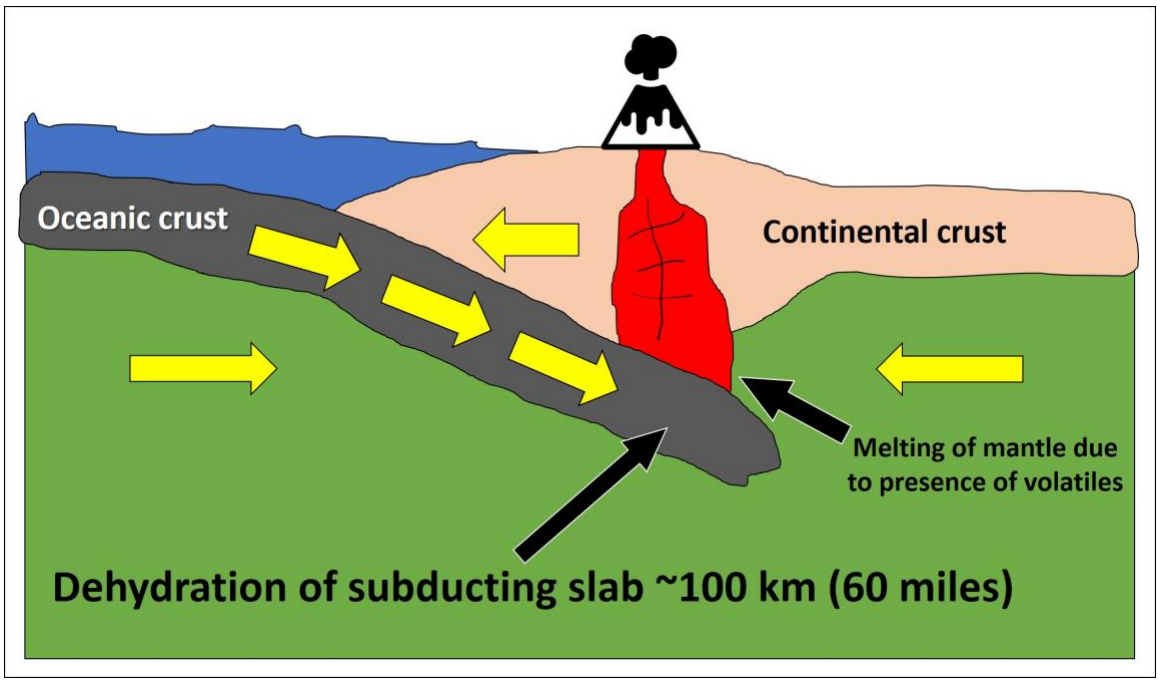


Figure 7.4: An illustration depicting the addition of volatiles, primarily water, at a subduction zone, resulting in melting.

Attributions

- Figure 7.2: Derivative of “Partial Melting Asthenosphere EN” (CC-BY-SA 3.0; Woudloper, via https://commons.wikimedia.org/wiki/File:Partial_melting_asthenosphere_EN.svg) by Emily Haddad
- Figure 7.3: “Decompression Melting” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 7.4: “Addition of Volatiles” (CC-BY 4.0; Chloe Branciforte, own work)

Composition

Composition of Magma

Remember that before an igneous rock can form, there must be molten material known as magma or lava. Most rocks (with very few exceptions) contain minerals that are crystalline solids composed of the chemical elements. From Chapter 3, recall that the most common minerals belong to a group known as the **silicate minerals**, which are abundant in the rocks of the lithosphere and mantle. Magma that forms from melt in these layers of the Earth also contain these same silicate minerals. All minerals, not just the silicates, are characterized by a certain set of conditions, such as temperature, at which they can melt. Recall that rocks are an aggregate or mixture of minerals. Oftentimes this can result in only some of the minerals in a rock melting, while others stay solid. Temperature conditions are important, as only minerals that melt at "lower" temperatures (590°C/1100°F) may experience melting, whereas the temperature would have to increase (for example, to 1150°C/2100°F) in order for other minerals to also melt. At these higher temperatures, even the lower temperature minerals are still melting and thus adding their chemical components to the magma generated. Even if the same types of rocks are melting, different magma compositions are generated by melting at different temperatures; we refer to this as magma evolution.

Magma is more buoyant than the source rock that generated it, and will eventually start to rise upward through the Earth's lithosphere. This separation of the magma from the source region will result in new thermal conditions. The magma moves away from the heated portion of the lithosphere and encounters cooler rocks, which results in the magma also cooling. As with melting, minerals also have a certain set of conditions at which they form, or crystallize, from a cooling melt. You would be right in thinking that the sequence of mineral crystallization is the opposite sequence of crystal melting. The sequence of mineral formation from magma was experimentally determined by Norman L. Bowen in the early 1900's, and the now famous **Bowen's Reaction Series** appears in countless textbooks and lab manuals (including this one!; **Figure 7.5**).

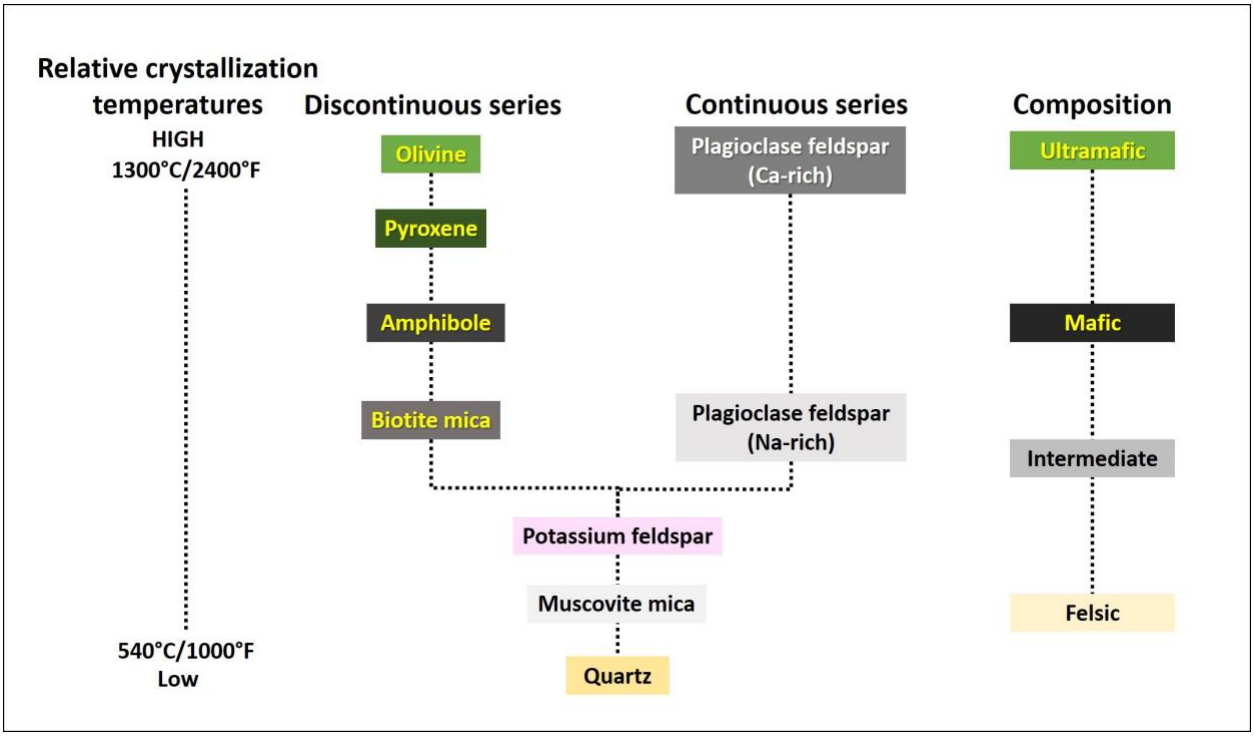


Figure 7.5: Bowen's Reaction Series. At higher temperatures, associated with ultramafic, mafic and intermediate magmas, the general progression can be separated into two branches. The continuous branch describes the evolution of the plagioclase feldspars as they evolve from being calcium-rich to more sodium-rich. The discontinuous branch describes the formation of mafic minerals: olivine, pyroxene, amphibole, and biotite mica.

This "reaction series" refers to the chemical reactions that form the minerals, through chemical bonding of elements within the magma, in a sequence that is based on falling magma temperatures. Close examination shows that the first mineral to crystallize in a cooling magma of ultramafic composition is **olivine**. Once temperatures fall below a specific range, olivine crystals will no longer form; instead, other minerals such as **pyroxene** will start to crystallize (a small interval of temperatures exists where both olivine and pyroxene can crystallize). Minerals that form in cooling magma are called crystals. As these crystals are forming, they are removing chemical elements from the magma. For example, olivine crystals take magnesium (Mg) and iron (Fe) from the magma and incorporate them into their crystal structure. This behavior of mineral crystals to take certain chemical elements into their structure, while excluding other elements, means that the composition of the magma must be changing as crystals are forming. This is why magmas continuously evolve: their chemistry is always changing.

There can be more than one mineral type crystallizing within the cooling magma. The minerals on the left side of Bowen's Reaction Series are referred to as a **discontinuous series**, as these minerals (olivine, pyroxene, amphibole, and biotite) all remove the iron (Fe), magnesium (Mg), and manganese (Mn) from the magma during crystallization, but do so at certain temperature

ranges. These iron- and magnesium-rich minerals are referred to as the **ferromagnesian silicates** (ferro = iron) and are typically green, dark gray, or black in color due to the absorption of visible light by the iron and magnesium atoms. On the right side of Bowen's reaction plagioclase crystallizes over a large temperature interval and represents a **continuous series** of crystallization even though its composition changes from calcium (Ca) rich to sodium (Na) rich. As the magma temperature drops and plagioclase first starts to crystallize (form), it will take in the calcium atoms into the crystal structure, but as magma temperatures continue to drop, plagioclase takes in sodium atoms preferentially. As a result, the higher temperature calcium-rich plagioclase is dark gray, in color due to the high calcium content (anorthite, or labradorite if also iridescent). The lower temperature sodium-rich plagioclase is white or lighter gray due to the high sodium content (albite).

Plagioclase Group Minerals		
Mineral name	**% Albite (Na-rich)**	**% Anorthite (Ca-rich)**
Albite	100-90	0-10
Oligoclase	90-70	10-30
Andesine	70-50	30-50
Labradorite	50-30	50-70
Bytownite	30-10	70-90
Anorthite	10-0	90-100

Table 7.1: Plagioclase group minerals and their percentage of sodium (Na) and calcium (Ca).

Finally, at the bottom of Bowen's Reaction Series, we see three more minerals form as temperatures continue to drop. These minerals (potassium feldspar, muscovite, and quartz) are considered to be "low temperature minerals", as they are the last to form or crystallize during cooling; conversely these three minerals are the first to melt as a rock is heated. The removal of iron and magnesium from the magma (minerals of the discontinuous series) results in the formation of these last three minerals and magma that is deficient in these chemical elements. Oftentimes, these minerals are referred to as the **nonferromagnesian silicates**, because they lack iron and magnesium and are considerably lighter in color; for example, potassium-rich feldspar (also known as K-feldspar or K-spar) can be pink, white, or beige in color.

Potassium Feldspar (K-feldspar) Group Minerals	
Mineral name	**Chemical formula**
Sanidine	$KAlSi_3O_8$
Orthoclase	
Microcline	

Table 7.2: The potassium feldspar group minerals.

The reference to mineral color is necessary, because the color of any mineral is primarily due to the chemical elements present in the mineral. *Therefore, the color of an igneous rock will be dependent on the mineral content (or chemical composition) of the rock*.

Igneous Rock Composition

Bowen's Reaction Series also includes the igneous rock compositions, which are entirely dependent on the minerals that compose that rock. For example, you can expect to find abundant olivine, and maybe a little pyroxene and a little Ca-rich plagioclase, in an ultramafic rock called peridotite or komatiite. Pyroxene, plagioclase, amphibole, and possibly some olivine may be present in a mafic rock such as gabbro or basalt. You would expect to see quartz, muscovite, potassium feldspar, and maybe a little biotite and Na-rich plagioclase in a felsic (or silicic) rock such as granite or rhyolite.

The classification of an igneous rock depends partly on the minerals that may be present in the rock. Since the minerals have certain colors due to their chemical makeup, then the rocks must also have certain colors. For example, a rock composed mostly of olivine will be green in color (like Mountain Dew) due to olivine's green color; such a rock would be considered to have an **ultramafic** composition. A rock that has a large amount of ferromagnesian minerals in it will be dark-colored, because the ferromagnesian minerals (besides olivine) tend to be dark colored. An igneous rock that is dark in color is referred to as having a **mafic** composition ("ma-" comes from magnesium, and "fic" from ferric iron). An igneous rock with a large amount of nonferromagnesian minerals will be lighter in color; these are termed **silicic** or **felsic** in composition ("fel" from feldspar, and "sic" from silica-rich quartz). A rock with a composition of **intermediate**, will fall between mafic and felsic. Using color, we'll be able to properly identify

any crystalline igneous rock (i.e. a rock contains crystals or minerals). Non-crystalline igneous rocks require a bit more information. As previously mentioned, classifying rocks into one of the igneous rock compositions (ultramafic, mafic, intermediate, and felsic) depends on the minerals that each rock contains.

An easy method of determining igneous rock composition is through determining the percentage of dark-colored minerals in the rock, without trying to identify the actual minerals present; this method of classification relies on a **mafic color index** (MCI), where the term mafic refers to any dark gray, black or green colored mineral. Igneous rocks with 0-15% dark colored minerals (or 0-15% MCI) are felsic. Igneous rocks with 46-85% MCI are mafic. Igneous rocks with over 85% MCI are considered ultramafic. This means that any rock with between 16-45% MCI has an intermediate composition.

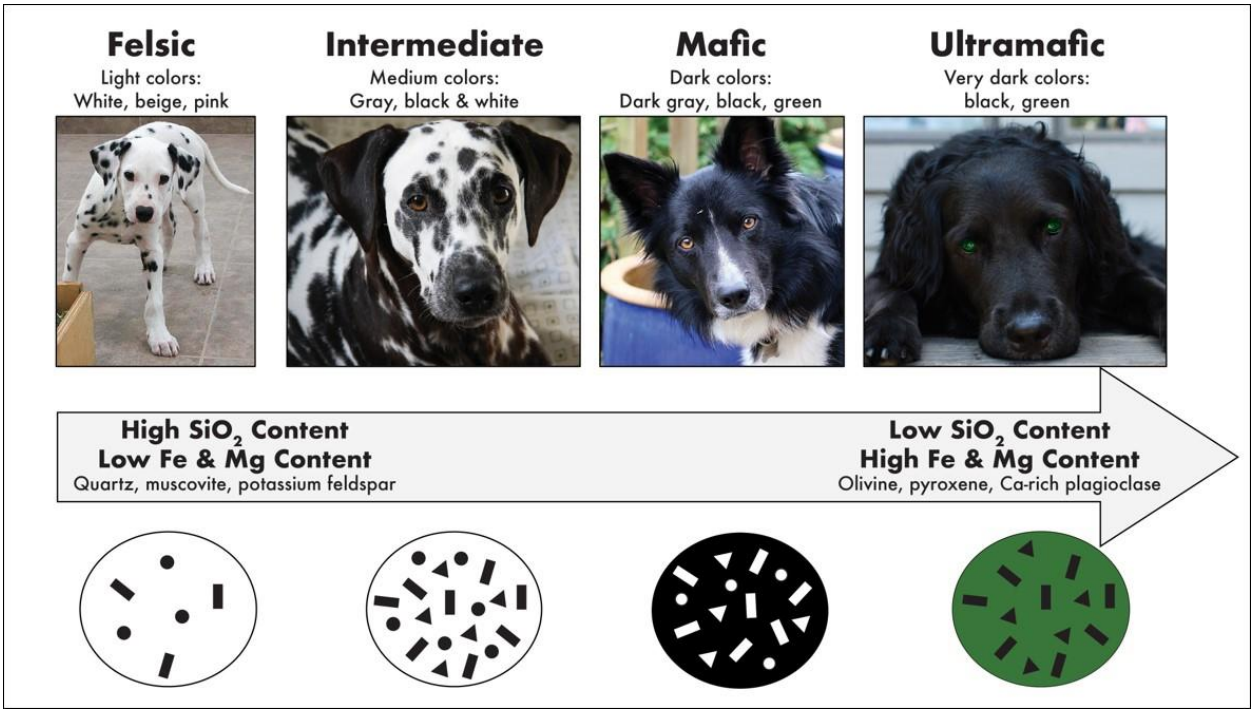


Figure 7.6: The mafic color index and its application to igneous compositions.

Estimating the percentage of dark-colored minerals is only possible if the minerals are large enough to see. In general, we can distinguish a mafic rock by its dark-colored appearance and a felsic rock by its light-colored appearance. An intermediate rock will be somewhat lighter than a mafic rock, yet darker than a felsic rock. Finally, an ultramafic rock is typically green in color, due to the large amount of olivine or pyroxene in the rock. Rocks that contain minerals that are too small to be seen can still be distinguished between ultramafic, mafic, intermediate and felsic by their overall color (**Table 7.3**).

Mafic Color Index (MCI)				
Composition	**% of mafic minerals**	**Overall color**	**Aphanitic (extrusive)**	**Phaneritic (intrusive)**
Felsic	0-15	Light - pink, white, beige	Rhyolite Trachyte	Granite Syenite Monzonite
Intermediate	16-45	Gray, green	Dacite Andesite	Granodiorite Diorite
Mafic	46-85	Dark - black, green, grey	Basalt	Gabbro
Ultramafic	>85	Green (olivine)	Komatiite	Peridotite

Table 7.3: The mafic color index.

Attributions

- Figure 7.5: “Bowen’s Reaction Series” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 7.1: “Plagioclase Group Minerals” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 7.2: “Potassium Feldspar Group Minerals” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 7.6: Derivative of (“Dalmatian Puppy” (CC-BY-SA 3.0; Carlos Estrada Dejo via Wikimedia Commons) and “Angies Bettellick” (CC-BY 2.0; Maja Dumat via Flickr) and “Border Collie, Shadow, Black & White Coat, Ireland” (CC-BY-SA 3.0; Jimbobrimbaud via Wikipedia) and “Reclining Black Dog” (CC-BY 2.0; Joe Parks via Wikimedia Commons)) by Emily Haddad and Chloe Branciforte.
- Table 7.3: “Mafic Color Index” (CC-BY 4.0; Chloe Branciforte, own work)

Texture

What Happens to a Melt As It Cools?

As a melt cools, minerals crystallize and glasses can develop. In general, melts will cool slowly, over millennia to millions of years (beyond a human lifespan), or rapidly, in seconds to decades (within a human lifespan). There are a number of factors that dictate the cooling rate of a melt, but the major control is the cooling environment or realm of the melt. Does the melt cool intrusively, as magma? Or does the melt cool extrusively, as lava? A melt that cools in the **intrusive,** or **plutonic**, realm cools slowly over millennia to millions of years. A melt that cools in the **extrusive,** or **volcanic**, realm cools rapidly, in seconds to decades. The extrusive realm is typically associated with volcanics, and if humans are present they may witness the eruption. The cooling realm is typically the driving factor of the rock's texture. Generally, rocks that cool intrusively have visible crystals (minerals), whereas rocks that cool extrusively have microscopically small crystals (minerals) or contain glass. In addition to the cooling realm, the size and shape of the melt will also dictate the overall cooling rate (**Figure 7.7**).

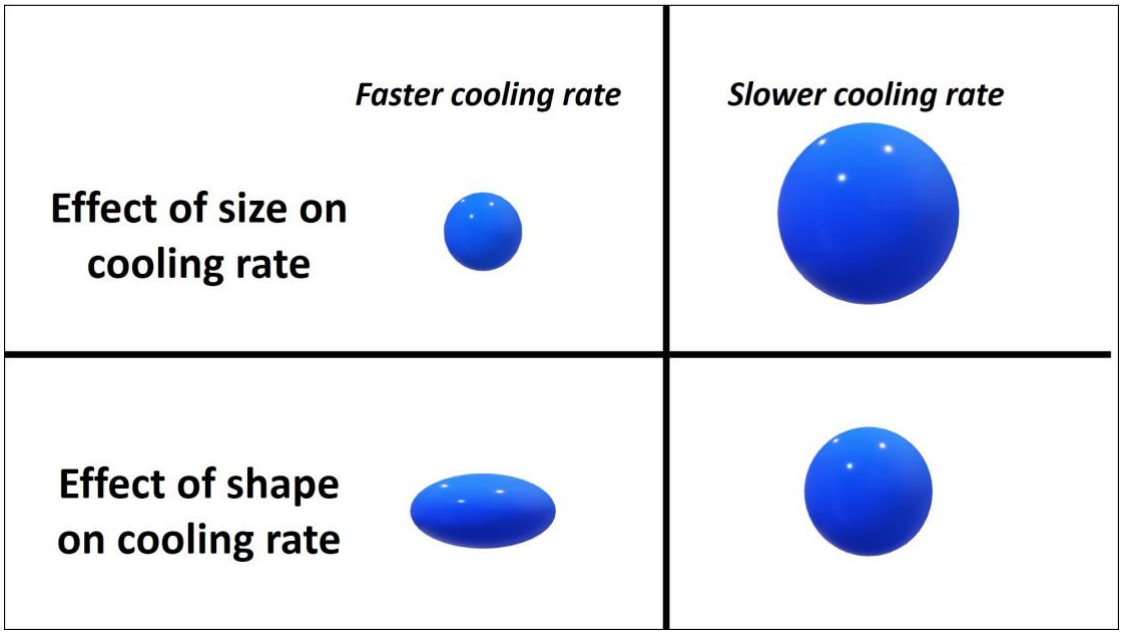


Figure 7.7: An illustration depicting the effect of size and shape on cooling rate.

The end product of a cooling melt is an igneous rock. This rock may contain minerals, glasses, clasts, or some combination of those materials.

The classification of igneous rocks is based not just on composition, but also on texture. Recall a rocks' **texture** refers to the *size and arrangement of minerals, glass, fragmented material, or vesicles (holes)*.

Igneous Rock Textures

Crystals form while the magma is cooling. Therefore, the size of the crystals is related to the cooling process. Each mineral derives its chemical composition directly from the magma and has a certain temperature interval during which that particular mineral can form. The chemical elements that become part of the mineral must migrate from the liquid magma to link or bond with other elements in a certain way to form the crystal structure that is unique for that mineral. Whether the magma's temperature drops quickly or slowly affects the time necessary for the migration of the chemical elements to form a mineral crystal.

When magma cools slowly, there is plenty of time for the migration of the needed chemical elements to form a certain mineral; that particular mineral can become quite large in size, large enough for a person to see without the aid of a microscope. As a result, this igneous rock with its visible minerals is said to have a **phaneritic texture** (phaneros = visible) (**Figure 7.8**). **Granite**, **diorite**, and **gabbro** are all phaneritic igneous rocks with different compositions (felsic, intermediate, and mafic, respectively).

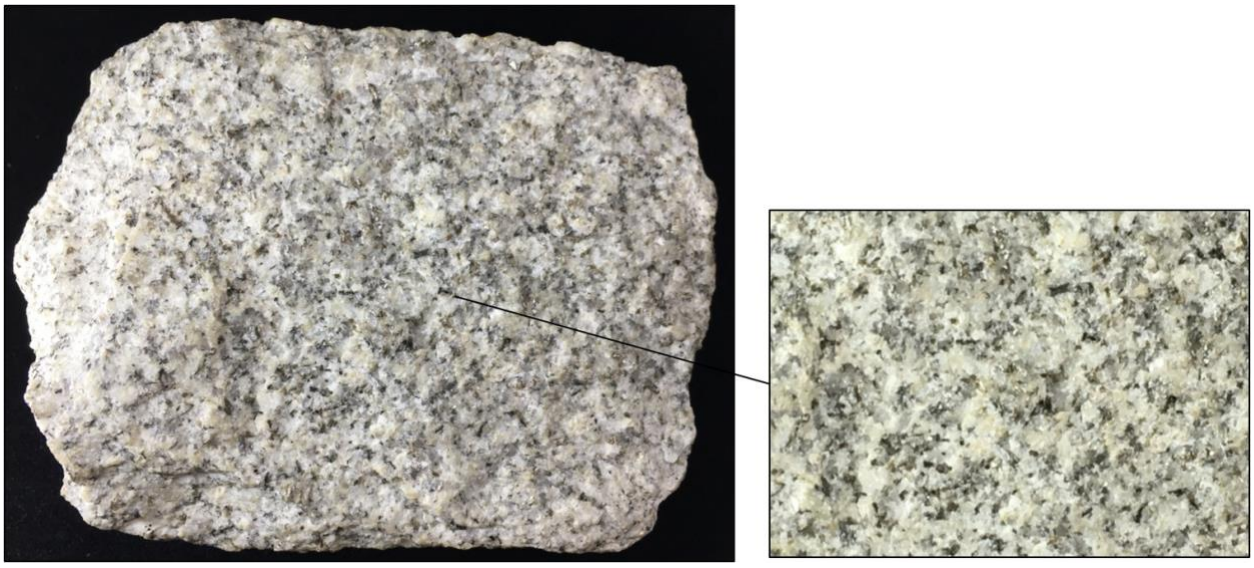


Figure 7.8: A phaneritic (coarse-grained) igneous rock.

If the rock contains crystals that are larger than your thumbnail, throughout the entire rock, the textural term is **pegmatitic** that forms a rock called **pegmatite** (**Figure 7.9**).

Figure 7.9: A pegmatitic igneous rock.

Magma that cools relatively quickly has less time for the migration of the chemical elements to form a mineral, and as a result the minerals will not have time to form large crystals. Therefore, many small crystals of a particular mineral will form in the magma. Igneous rocks that are composed of crystals too small to see (unless you have a microscope) are called **aphanitic** igneous rocks (**Figure 7.10**).

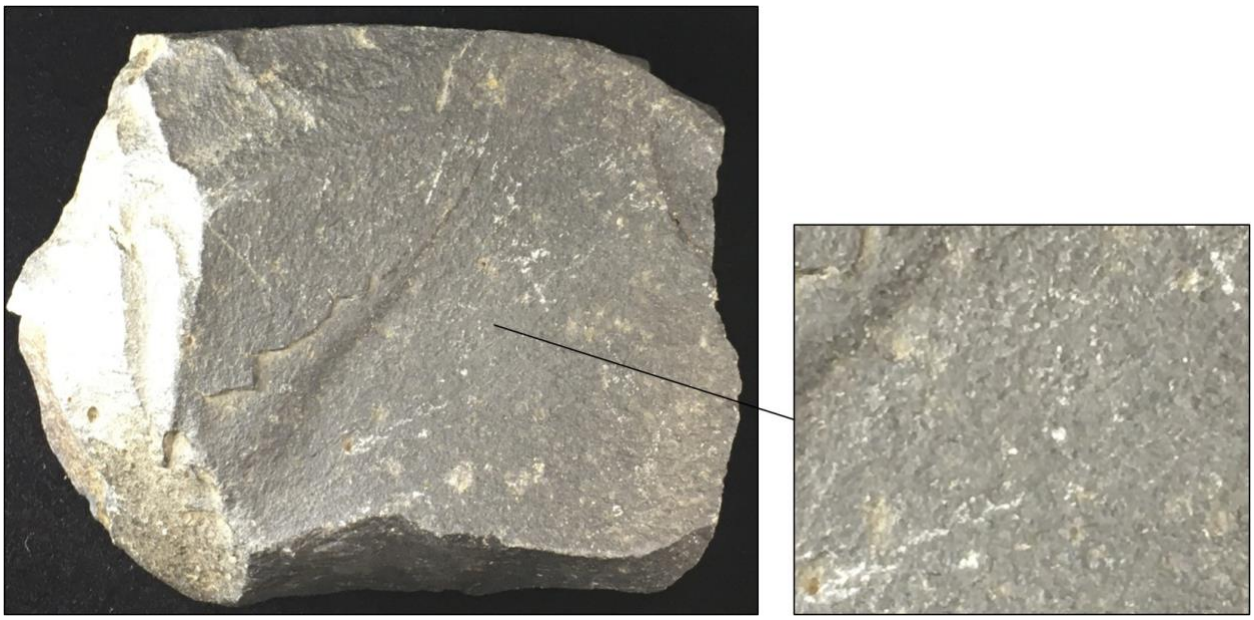


Figure 7.10: An aphanitic igneous rock.

Basalt, **andesite**, and **rhyolite** are all aphanitic igneous rocks with different compositions (mafic, intermediate, and felsic, respectively). It is important to note that basalt and gabbro

both have the same composition – mafic – but one rock represents a lava that cooled fast (basalt), and the other represents a mafic magma that cooled slowly (gabbro). The same can be said for the other rock compositions: the felsic rocks rhyolite and granite have identical compositions, but one cooled fast (rhyolite) and the other cooled slowly (granite). The intermediate rocks diorite and andesite also represent melts that cooled slower or more rapidly, respectively.

Sometimes there are some visible crystals in an otherwise aphanitic rock, such as the andesite shown; this texture is referred to as **porphyritic** (or more accurately porphyritic-aphanitic; **Figure 7.11**). Two different crystal sizes within the same igneous rock indicates that the cooling rate was complex, and there may be multiple levels of cooling represented. The larger crystals are called **phenocrysts** and the smaller crystals are called the **groundmass**. While the magma was cooling slowly, larger crystals can form. If the magma moves upward and erupts from a volcano, the remaining lava crystallizes quickly around the already formed phenocrysts, to form the small-size crystals in the groundmass. A phaneritic rock can also be referred to as a porphyritic-phaneritic if it contains some very large crystals (phenocrysts), in addition to the other smaller, but still visible crystals in the groundmass.

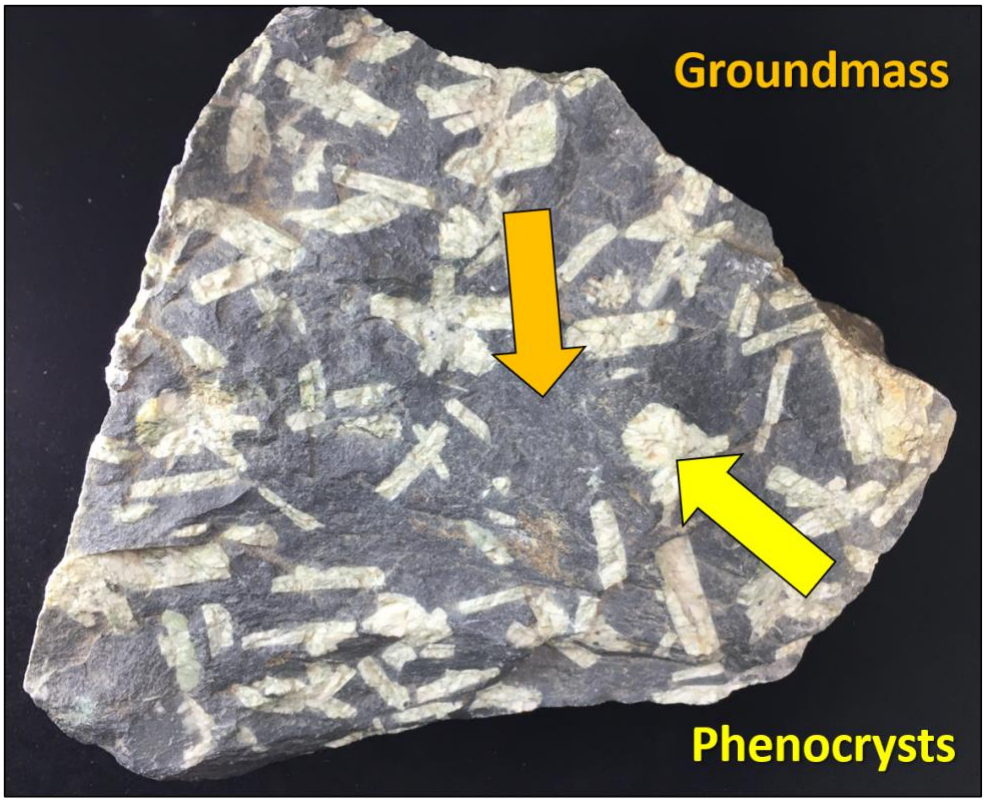


Figure 7.11: A porphyritic igneous rock. Phenocrysts, the white minerals, are labeled with the yellow arrow. Goundmass, fine-grained gray regions, are labeled with the orange arrow.

Sometimes the melt cools so quickly that there isn't time to form *any* minerals, as the chemical elements in the magma do not have time to migrate into any crystal structure. When this happens, the magma becomes a dense glass called **obsidian**. By definition, glass is a chaotic arrangement of the chemical elements, and therefore is not considered to be a mineral; igneous rocks composed primarily of glass are said to have a **glassy texture** (**Figure 7.12**). The identification of a glassy rock such as obsidian is easy once you recall the properties of glass: any thick glass pane or a glass bottle that is broken will have a smooth, curve-shaped pattern on the broken edge called **conchoidal fracture**. Even though obsidian is naturally occurring, and not synthetic (human-made), it still breaks in the same way as glass you are likely familiar with. Obsidian appears quite dark in color because light has difficulty passing through the dense glass; however, chemically it is mostly silicon and oxygen and therefore more felsic in composition.

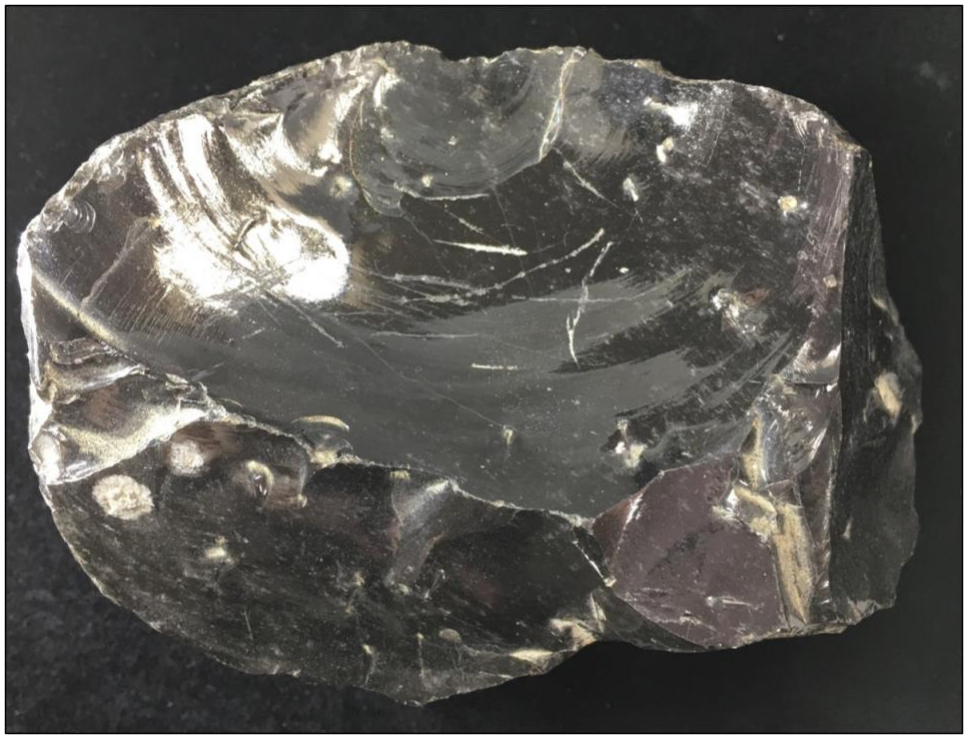


Figure 7.12: A glassy igneous rock.

Another igneous rock that is also composed primarily of glass is called pumice, which will actually float on water due to its low density. The glass in this rock has been aerated during a volcanic eruption. This aeration produces a texture referred to as **vesicular** or **porous**, and the rock typically has many holes (imagine freezing the foamy head on root beer) (**Figure 7.13**). **Pumice** can display a wide range of colors but typically has a composition between felsic to intermediate. **Scoria**, the other vesicular rock, will not float on water. This is because scoria

contains an abundance of iron and magnesium, resulting in a dark gray, black or red color, representing a more mafic composition.

Figure 7.13: A vesicular igneous rock.

The final texture is unique in that the rock contains clasts, fragments, or pieces of pre-existing rock that were violently produced during an explosive, gas-rich, volcanic eruption. This texture is termed **pyroclastic or fragmental** (**Figure 7.14**) and has a distinct gritty or grainy feel.

Figure 7.14: A fragmental igneous rock.

The different crystal sizes and presence or absence of glass in an igneous rock is primarily controlled by the rate of magma cooling. Generally, rocks that cool intrusively have visible crystals (minerals), whereas rocks that cool extrusively have small crystals (minerals) or contain no crystals, instead exhibiting glasses, holes, or clasts. Recall, magmas that cool below the surface in the **intrusive** or **plutonic realm** cool slowly over millennia to millions of years, because the rock surrounding the magma acts as an insulator (similar to a coffee thermos). Lavas that cool at the surface, in the **extrusive** or **volcanic realm**, cool rapidly, in seconds to decades.

Texture	**Composition**			
	Felsic High SiO2 Low Fe & Mg	**Intermediate**	**Mafic**	**Ultramafic** Low SiO2 High Fe & Mg
Minerals present (crystalline rocks only)	*Quartz, Potassium feldspar, Na-rich plagioclase feldspar*	*Na-rich plagioclase feldspar, Amphibole*	*Ca-Plagioclase feldspar, Pyroxene*	*Olivine, Pyroxene, Ca-Plagioclase feldspar*
Pegmatite*	Granite pegmatite	--	Gabbro pegmatite	--
Phaneritic*	Granite Syenite Monzonite	Diorite	Gabbro	Peridotite
Porphyritic*^	Granite porphyry Rhyolite porphyry	Andesite porphyry	Basalt porphyry	--
Aphanitic^	Rhyolite Trachyte	Andesite Dacite	Basalt	Komatiite
Glassy^	Obsidian		--	--
Vesicular^	Pumice		Scoria	--
The rocks below have no set igneous composition. Instead, the size of the fragments (clasts) are used to identify.				
Pyroclastic^ (Fragmental)	Fine (<4 mm)	Volcanic Tuff		
	Coarse (>4 mm)	Volcanic Breccia		
***intrusive** **^extrusive** ***^complex cooling history**				

Table 7.4: This chart helps classify igneous rocks using both their texture and composition.

Attributions

- Figure 7.7: “Cooling Rate” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 7.8: “Phaneritic Texture” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 7.9: “Pegmatite Texture” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 7.10: “Aphanitic Texture” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 7.11: “Porphyritic Texture” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 7.12: “Glassy Texture” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 7.13: “Vesicular Texture” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 7.14: “Fragmental Texture” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 7.4: “Igneous Rock Chart” (CC-BY 4.0; Chloe Branciforte, own work)

Intrusive Igneous Features

Once the magma has completely crystallized, an intrusive igneous body is formed that can be generally called a **pluton** regardless of its shape or size. Sometimes these plutons are exposed at the Earth's surface where direct observation of the rock is possible. They are composed of minerals that are large enough to see without the aid of a microscope. This is why any igneous rock that has visible crystals throughout (phaneritic, porphyritic-phaneritic, or pegmatitic) can be referred to as a plutonic rock.

Figure 7.15: The Sierra Nevada Mountains of eastern California. The batholith is a suite of intrusive igneous rocks representing old, cooled magma chambers that were originally beneath an ancient chain of subduction zone volcanoes. The rocks are mostly Cretaceous-aged granite and granite-like lithologies such as granodiorite. Some sedimentary and metamorphic rocks are present, representing roof rocks and altered roof rocks above the original magma chambers.

A **batholith** is a large area (>100 square km) that consists of numerous types of plutons. Here in California, there are many famous batholith examples including the **Sierra Nevada batholith**, visible in **Yosemite National Park** (**Figure 7.15**), **Peninsular Range batholith**, visible around the San Diego area and south into Baja California, and the **Klamath Batholith,** visible in northern California along the border with Oregon.

Sills and Dikes are tabular bodies of magma that intrude into a fracture. **Sills** follow bedding planes, whereas **dikes** cross-cut beds (**Figure 7.16**). Tabular (sheet-like) plutons are distinguished on the basis of whether or not they are concordant with (parallel to) existing layering (e.g., sedimentary bedding or metamorphic foliation) in the country rock. A sill is concordant with existing layering, and a dike is discordant. If the country rock has no bedding or foliation, then any tabular body within it is a dike. Note that the sill-versus-dike designation is not determined simply by the orientation of the feature. A dike can be horizontal and a sill can be vertical (if the bedding is vertical). A **laccolith** is a sill-like body that has expanded upward by deforming the overlying rock (**Figure 7.16**). A **stock** is a discordant (cuts across other layers), balloon-shaped intrusive rock body (< 100 square km) that is sometimes [confusingly] also called a pluton.

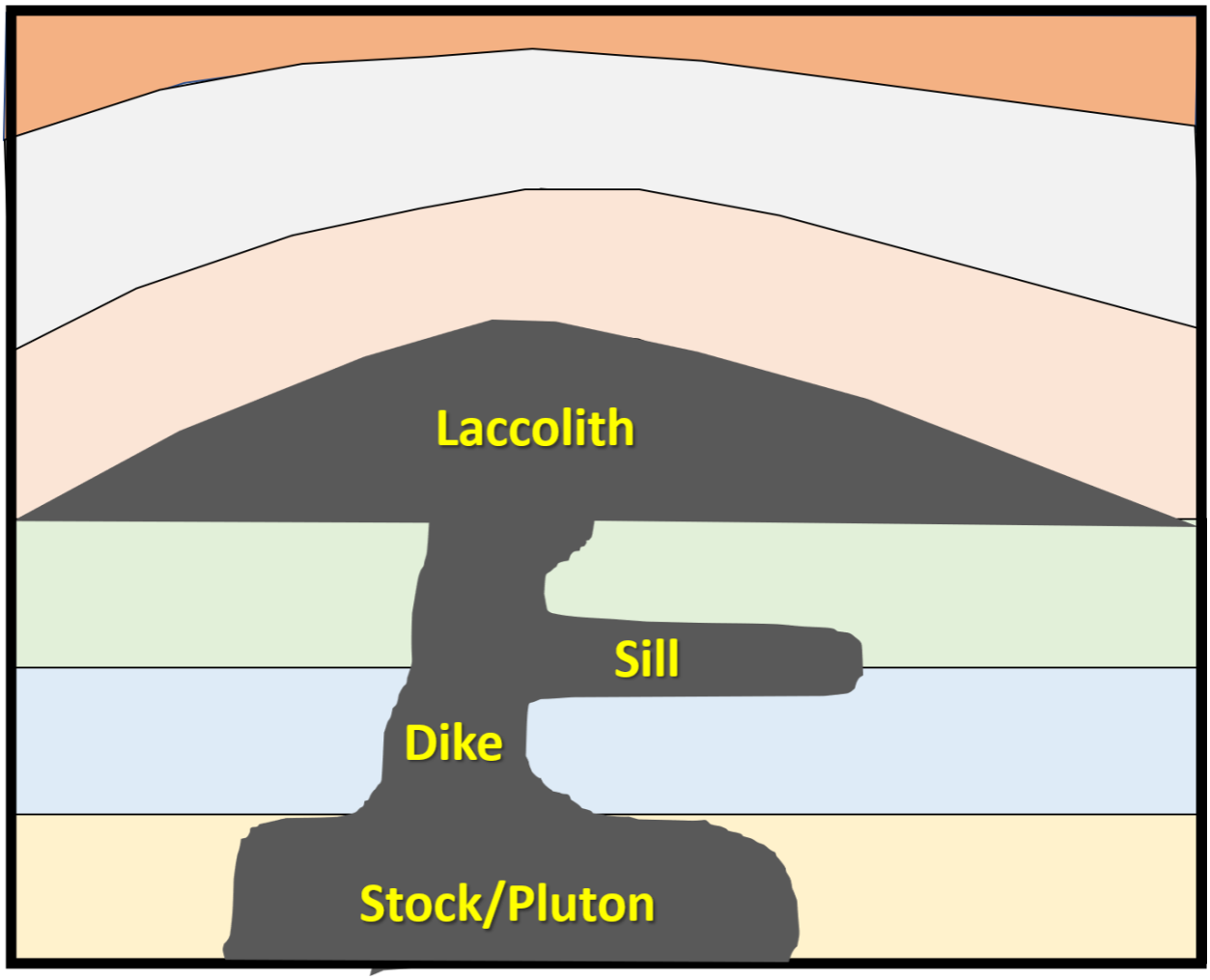


Figure 7.16: Intrusive igneous features.

Attributions

- Figure 7.15: “Sierra Nevada Batholith” (CC-BY 2.0; James St. John via Flickr)
- Figure 7.16: “Intrusive Igneous Features” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 7A: The Mafic Color Index (MCI)

For this section you will need igneous rock samples selected by your instructor. Locate these samples before you begin.

Take a close look at the rocks; how are they different? When you hold them closer to a light source, do you notice if they reflect light? Are they dull looking? Have small shiny surfaces? Are they extremely shiny and smooth? Have holes?

Separate the samples into three groups based on their color (dark, light or intermediate), as a first attempt at classifying rock compositions based on color.

1. Select the correct sample provided by your instructor. Indicate the mafic color index (MCI)?
    - **a.** 0-15% MCI (felsic)
    - **b.** 16-45% MCI (intermediate)
    - **c.** 46-85% MCI (mafic)
    - **d.** >85% MCI (ultramafic)

2. Using the same sample from above, examine the pink colored minerals present. Which mineral is this?
    - **a.** Quartz
    - **b.** Biotite
    - **c.** Ca-rich plagioclase
    - **d.** Potassium feldspar

3. Using the same sample from above, examine the small, dark colored minerals present. Which mineral is this?
    - **a.** Quartz
    - **b.** Biotite
    - **c.** Ca-rich plagioclase
    - **d.** Potassium feldspar

4. Select another sample provided by your instructor. Indicate the mafic color index (MCI)?
    - **a.** 0-15% MCI (felsic)
    - **b.** 16-45% MCI (intermediate)
    - **c.** 46-85% MCI (mafic)
    - **d.** >85% MCI (ultramafic)

5. Using the same sample from above, examine the white colored minerals present. Which mineral is this?
    - **a.** Quartz
    - **b.** Biotite
    - **c.** Ca-rich plagioclase
    - **d.** Potassium feldspar

6. Select the last sample provided by your instructor. Indicate the mafic color index (MCI)?
    - **a.** 0-15% MCI (felsic)
    - **b.** 16-45% MCI (intermediate)
    - **c.** 46-85% MCI (mafic)
    - **d.** >85% MCI (ultramafic)

7. Using the same sample from above, examine the green-colored mineral present. Which mineral is this?
    - **a.** Quartz
    - **b.** Biotite
    - **c.** Pyroxene
    - **d.** Olivine

8. According to Bowen's Reaction Series, this sample should start melting at what temperature?
    - **a.** ~2400 °F
    - **b.** ~2000°F
    - **c.** ~1500 °F
    - **d.** ~1000 °F

Activity 7B: Determining Igneous Textures

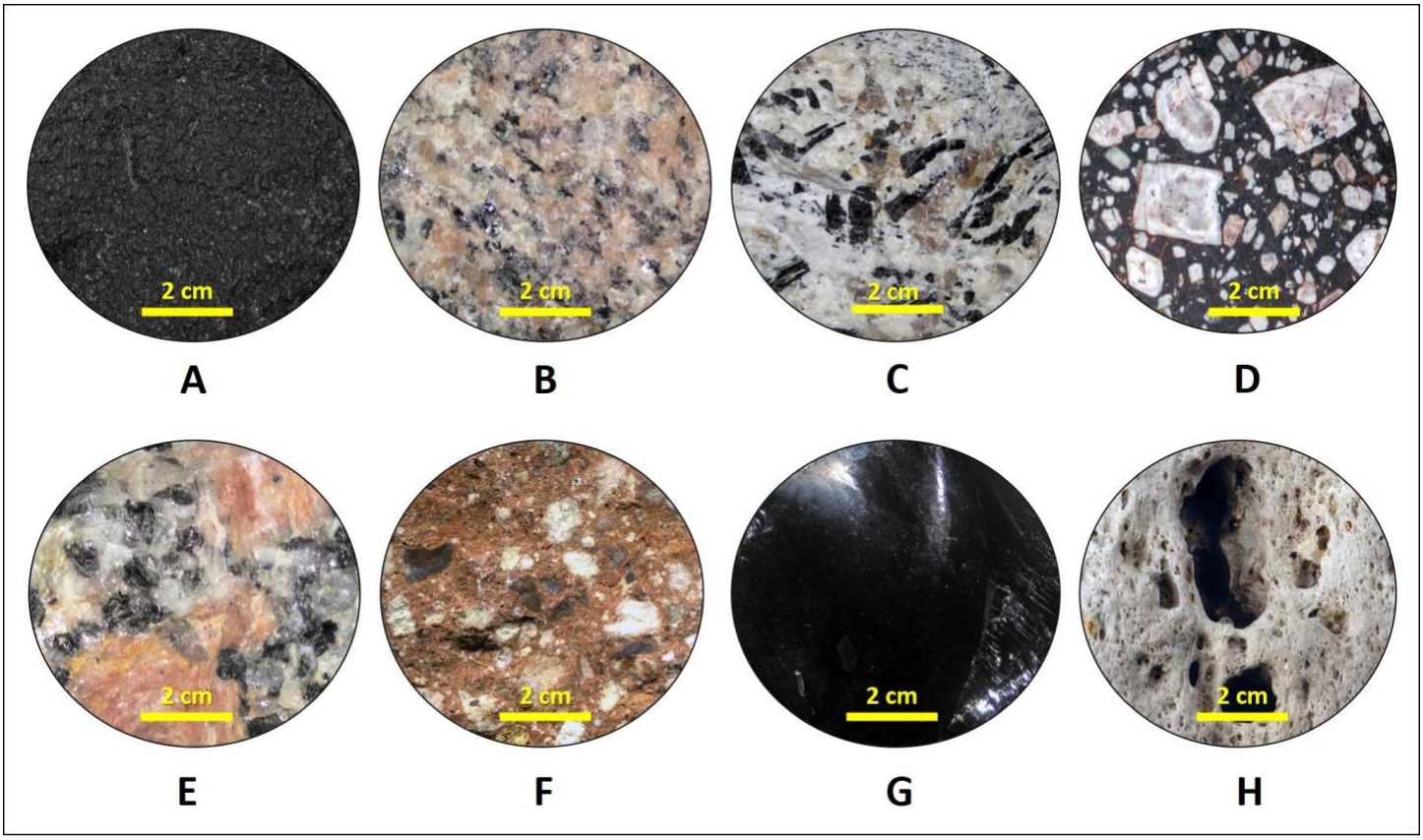


Figure 7.17: Activity 7B, determine the igneous textures of rocks A-H.

1. Determine the texture at A:
2. Determine the texture at B:
3. Determine the texture at C:
4. Determine the texture at D:
5. Determine the texture at E:
6. Determine the texture at F:
7. Determine the texture at G:
8. Determine the texture at H:

Attributions

- Figure 7.17: “Igneous Rock Textures” a Derivative of (CC-BY 2.0; James St. John via Flickr(A), Flickr(B), Flickr(C), Flickr(D), Flickr(E), Flickr(F), Flickr(G), and Flickr(H)) by Chloe Branciforte

Activity 7C: Determining Igneous Rock Compositions

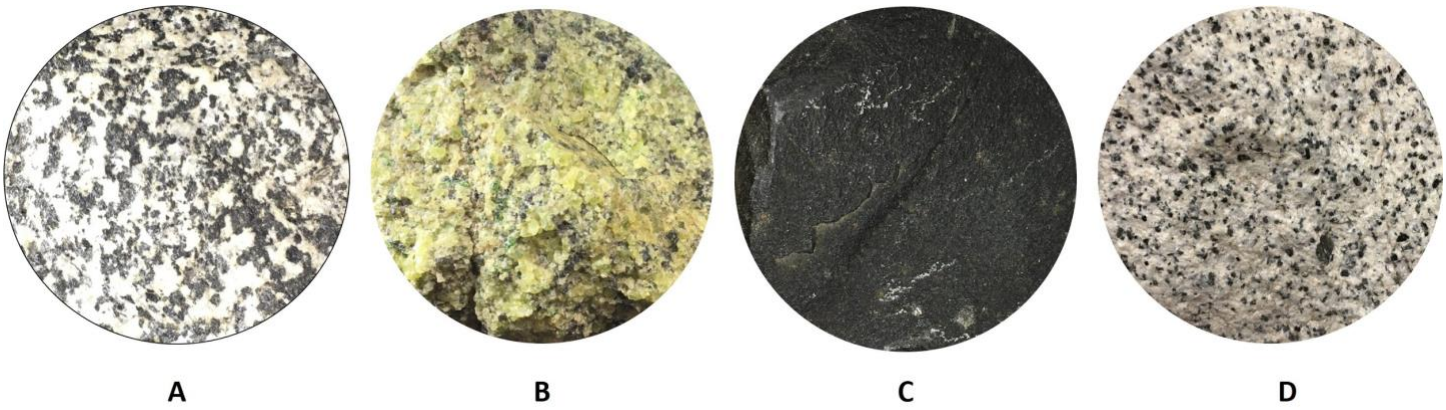


Figure 7.18: Activity 7C, determine the igneous compositions of rocks A-D.

1. For Rock A, determine:
    a. The relative percentage of SiO_2 vs. Fe and Mg:
    b. The Mafic Color Index and associated igneous composition:

2. For Rock B, determine:
    a. The relative percentage of SiO_2 vs. Fe and Mg:
    b. The Mafic Color Index and associated igneous composition:

3. For Rock C, determine:
    a. The relative percentage of SiO_2 vs. Fe and Mg:
    b. The Mafic Color Index and associated igneous composition:

4. For Rock D, determine:
    a. The relative percentage of SiO_2 vs. Fe and Mg:
    b. The Mafic Color Index and associated igneous composition:

Attributions

- Figure 7.18: “Igneous Compositions” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 7D: Determining Igneous Textures & Compositions from Samples

For this section, you will need igneous rock samples selected by your instructor. Locate these samples before you begin.

1. Select the first sample designated by your instructor. Is this sample composed mainly of crystals, holes, glass, or clasts?
    - **a.** Crystals
    - **b.** Holes
    - **c.** Glass
    - **d.** Clasts

2. What is the textural term for this sample?
    - **a.** Crystalline, aphanitic
    - **b.** Crystalline, phaneritic
    - **c.** Vesicular
    - **d.** Glassy
    - **e.** Pyroclastic or fragmental

3. What is the likely cooling history of this sample?
    - **a.** This sample cooled as magma, slowly, in the intrusive cooling realm.
    - **b.** This sample cooled as lava, quickly, in the intrusive cooling realm.
    - **c.** This sample cooled as magma, slowly, in the extrusive cooling realm.
    - **d.** This sample cooled as lava, quickly, in the extrusive cooling realm.

4. What is the overall color of this rock?
    - **a.** Green
    - **b.** Dark - dark gray, green, black
    - **c.** Gray
    - **d.** Light - pink, white, beige

5. What is the likely composition of this rock?
    - **a.** Felsic
    - **b.** Intermediate
    - **c.** Mafic
    - **d.** Ultramafic

6. Identify this igneous rock by name:

7. Select the next sample designated by your instructor. Is this sample composed mainly of crystals, holes, glass, or clasts?

- **a.** Crystals
- **b.** Holes
- **c.** Glass
- **d.** Clasts

8. What is the textural term for this sample?

- **a.** Crystalline, aphanitic
- **b.** Crystalline, phaneritic
- **c.** Vesicular
- **d.** Glassy
- **e.** Pyroclastic or fragmental

9. What is the likely cooling history of this sample?

- **a.** This sample cooled as magma, slowly, in the intrusive cooling realm.
- **b.** This sample cooled as lava, quickly, in the intrusive cooling realm.
- **c.** This sample cooled as magma, slowly, in the extrusive cooling realm.
- **d.** This sample cooled as lava, quickly, in the extrusive cooling realm.

10. What is the overall color of this rock?

- **a.** Green
- **b.** Dark - dark gray, green, black
- **c.** Gray
- **d.** Light - pink, white, beige

11. What is the likely composition of this rock?

- **a.** Felsic
- **b.** Intermediate
- **c.** Mafic
- **d.** Ultramafic

12. Identify this igneous rock by name:

Activity 7E: Identifying Igneous Rocks

Sample Number	Does the rock contain crystals, holes, glass, or clasts?	Texture	Cooling history *Intrusive or Extrusive? Slow or Rapid cooling?*	Overall color	Composition	Igneous Rock Name

Activity 7F: Igneous Rocks in Yosemite National Park

Watch this National Park Service video regarding the rocks and landscapes of Yosemite National Park. Next use the browser version of Google Earth, to visit the meadow at the base of El Capitan in Yosemite Valley. This Google view was taken using a 360° view camera. Using your mouse, pan around to examine the valley.

1. What is the overall cross-sectional shape of the valley?
    a. U-shape
    b. V-shape

2. What process likely formed this valley?
    a. River processes
    b. Glacial processes

El Capitan, Half Dome, and much of the valley and park is composed of igneous rock. Below is a picture of a hand sample of this rock. No magnification is necessary.

Figure 7.19: Activity 7F, close-up of an igneous rock from El Capitan and Half Dome in Yosemite National Park.

3. What is the likely composition of this igneous rock?
    a. Mafic
    b. Intermediate
    c. Felsic

4. Why did you select this composition?

5. What is the texture of this igneous rock?
    a. Aphanitic
    b. Phaneritic
    c. Vesicular
    d. Glassy
    e. Fragmental (pyroclastic)

6. Why did you select this texture?

7. Based on the composition and texture determined above, what is the name of this igneous rock?

Near Cathedral Peak in Yosemite National Park, the igneous rock looks slightly different. Below is a picture of a hand sample of this rock. No magnification is necessary.

Figure 7.20: Activity 7F, close-up of an igneous rock from near Cathedral Peak in Yosemite National Park.

8. What is the likely composition of this igneous rock?

- **a.** Mafic
- **b.** Intermediate
- **c.** Felsic

9. What is the texture of this igneous rock? *Be specific*.

10. Based on this texture, what term can be applied to the larger pink crystals?

11. Based on this texture, what term can be applied to the remaining smaller crystals?

12. Notice the large, pinkish crystals. Which mineral is represented by the pink color?

13. What is the name of this igneous rock?

Attributions

- Figure 7.19: “Yosemite Igneous Rock” (CC-BY 4.0; Roger Putnam, own work)
- Figure 7.20: “Granite” (CC-BY 2.0; James St. John via Flickr)

Chapter 8: Volcanoes and Volcanic Activity

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Relate magma type with plate boundaries.
- ✔ Recognize volcanic types and materials.
- ✔ Associate volcano form with eruption type and magma type.
- ✔ Recognize the hazards associated with volcanoes.

Thumbnail for Chapter 8:

Thumbnail: "Eruption from Manzanita Lake" (Public Domain; USGS)

Living with Volcanoes

A volcano is any mountain or vent through which volcanic materials surface. This definition is broad to encompass all the potential types of volcanoes.

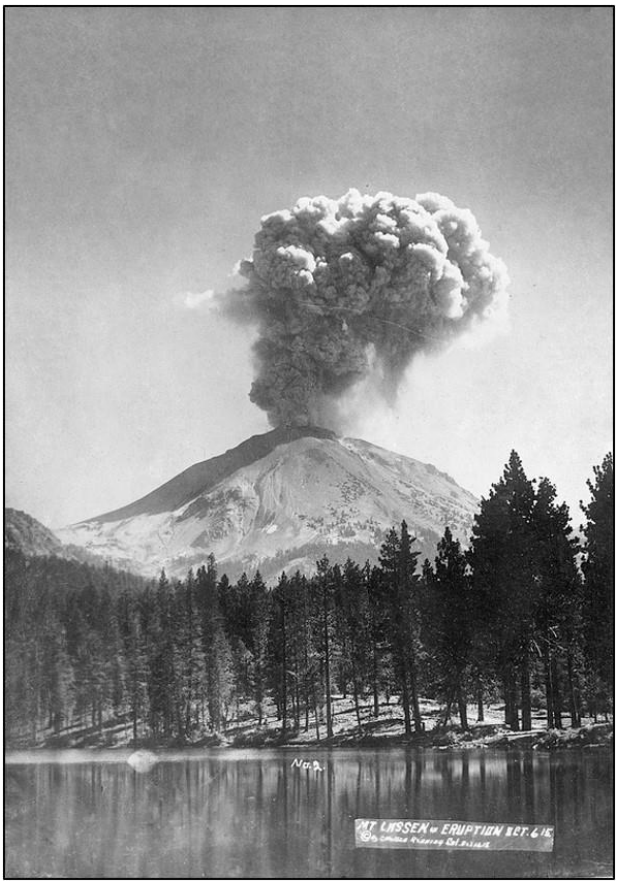


Figure 8.1: May 1915 eruption of Lassen Peak in northern California from Manzanita Lake. Read more about this eruption here.

Would you be willing to live near a volcano? Some of us will say "NO WAY!", while others may agree to a volcanic neighbor. Surprisingly, more than 500 million people live in areas at risk of a volcanic eruption. Some live on or near an **active volcano**, which has erupted in recent memory and may even be currently erupting (**Figure 8.1**; read more about the 1915 Lassen Peak eruption). Many more live near volcanoes that are considered **dormant**, experiencing a volcanically quiet period over the past 10,000 years but with the potential to erupt in the future. **Extinct volcanoes** are those that cannot erupt in the future, as their source of molten rock is no more.

Some of you may be thinking, "why would anyone live near an active volcano"?! Well, consider, why do you live in California? California is a geologically hazard-rich state: we have earthquakes, wildfires, landslides, volcanoes, tsunamis, sea-level rise, and much more. Why, then, do so many of us live here? It's likely that you work, live, and go to school here. For many, family are nearby; others stay due to financial situations. Some love the access to beaches, mountains, and/or the desert. In general, you have weighed the pros and cons and have opted to remain here in the Golden State. Hazards scientists refer to this decision as **acceptable risk**: weighing the benefits of our location against the likelihood of its hazards impacting us.

In terms of volcanic risk, not all volcanoes erupt explosively. For example, the type of volcano that forms the Hawaiian Islands erupts **effusively**, with lava running down the sides (flanks) of the volcano (**Figure 8.2**). Hawaiian citizens are familiar with this style of eruption and are aware

Figure 8.2: June 2018 eruption of Kilauea on the Big Island of Hawaii.

the volcano will not erupt explosively. However, these eruptions may still be destructive, as demonstrated by the 2018 eruption of Kilauea.

Explosive eruptions are more likely for the islands of Sumatra and Java or the volcanoes of the Pacific northwest (**Figure 8.3**). These volcanoes can be very dangerous, particularly for densely populated communities nearby. Because human settlements have been built around active and potentially explosive volcanoes, it is important to understand why these volcanoes are dangerous, while others, like those in Hawaii, carry less risk.

Figure 8.3: 2006 Eruption of Cleveland Volcano, Aleutian Islands, Alaska as viewed from the International Space Station (ISS). The ash plume is moving west-southwest from the summit vent.

A person who studies volcanoes is referred to as a volcanologist. A **volcanologist** is a geoscientist who studies volcanic processes, styles, and eruptions. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many of these geoscientists are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including in mining and natural resource extraction or in hazard mitigation and assessment. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy).

Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 8.1: “Eruption from Manzanita Lake” (Public Domain; USGS)
- Figure 8.2: “Kilauea Volcano – Fissure 8 Aerial” (Public Domain; USGS)
- Figure 8.3: “Eruption of Cleveland Volcano, Aleutian Islands, Alaska” (Public Domain; NASA)

Melt Composition

Recall that igneous rock classification is in part based on the chemistry or mineral content of the sample. Ultramafic rocks are igneous rocks composed primarily of olivine and a lesser amount of calcium-rich plagioclase and pyroxene, whereas felsic rocks are composed primarily of quartz, muscovite and potassium feldspar. Igneous rocks are the crystallized result of a cooled melt, and the minerals that form during cooling depend on the chemical composition of the melt. For example, a mafic magma will form a mafic rock containing a large amount of the ferromagnesian minerals pyroxene and amphibole, but will not contain quartz (the mineral that is always present in felsic rocks). We classify a rock according to its chemistry; likewise, in order to understand the type of volcano produced by a specific magma, we need to consider its chemistry.

Partial Melt Composition

Recall that magma is generated by partial melting of a source rock, and if we refer to **Bowen's Reaction Series** (**Figure 8.4**), we notice that minerals have different melting temperatures. If a rock undergoes partial melting, the minerals that melt are those minerals on the bottom of the Reaction Series that are rich in silica (SiO_2) and poor in iron and magnesium. This means that magma generated by partial melting will be richer in silica and contain less iron and magnesium than the source rock (the rock that partially melted). The different magma types (and the solid rock forms that they make) are listed in order of decreasing iron and magnesium, and increasing silica, with ultramafic rocks as the most iron and magnesium rich and silica poor, and felsic rocks as the most deficient in iron and magnesium but containing the most silica. Therefore, partial melting of a mantle rock that has an ultramafic composition will produce a mafic magma; likewise, partial melting of a mafic rock can produce an intermediate magma type, and partial melting of an intermediate rock can produce felsic magma.

There are other ways that felsic and intermediate magmas are produced; for example, magma that is moving upward (ascending) through the crust may melt and incorporate some of those crustal rocks, changing the magma's composition. Recall that the continental crust is the lowest density rock type of the Earth, of granitic composition, and quite thick at convergent plate boundaries; at convergent plate boundaries, magma may have to travel through this thick portion of the continental crust. At any time before the magma is completely crystallized, it can melt the surrounding crust and end up with a more silica rich composition. That means an intermediate or even a mafic magma will become more felsic as it travels through the continental crust.

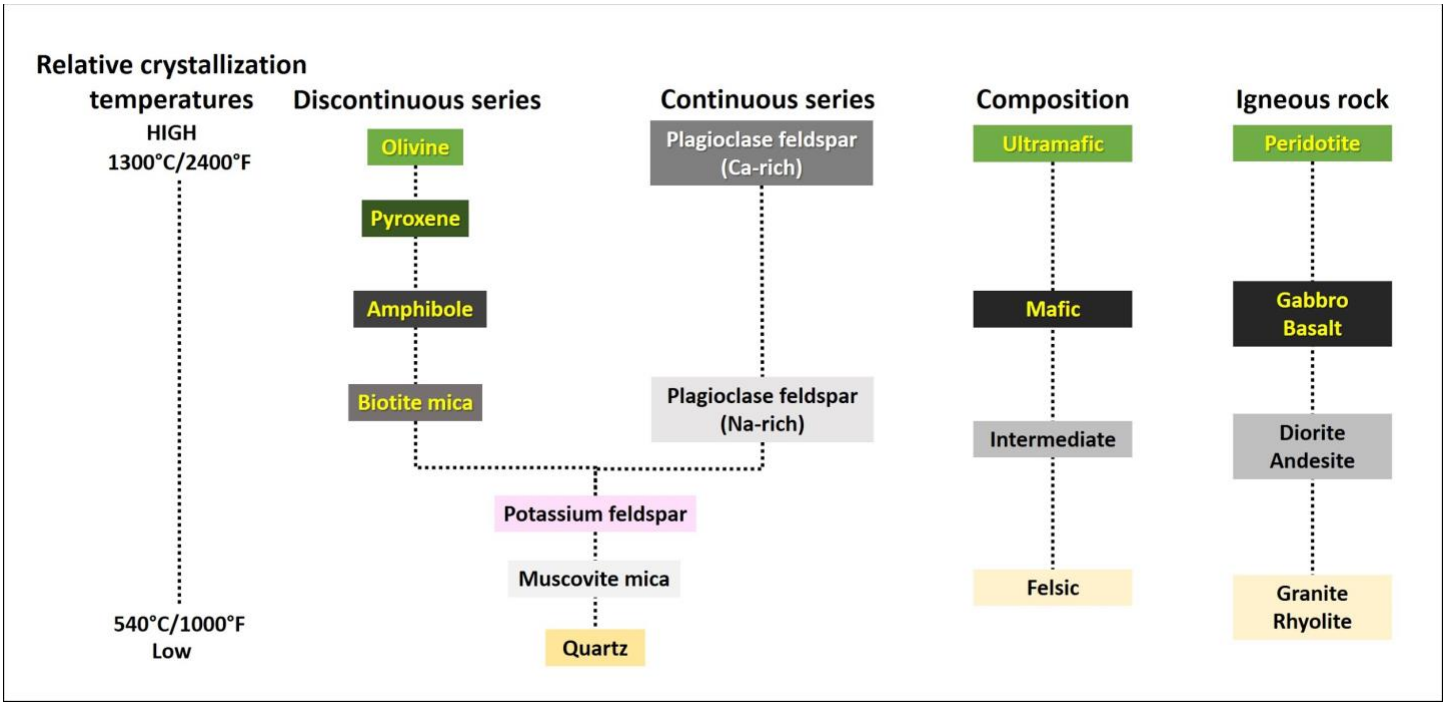


Figure 8.4: Bowen's Reaction Series. At higher temperatures that are associated with ultramafic, mafic and intermediate magmas, the general progression can be separated into two branches. Resultant rocks can also be determined.

While most magma crystallizes below ground, a portion of it does erupt onto the surface of the Earth, either as a passive lava flow or under more explosive conditions such as the May 1980 eruption of Mount St. Helens, WA. Whether the style of eruption is passive or active (explosive) depends on the magma composition.

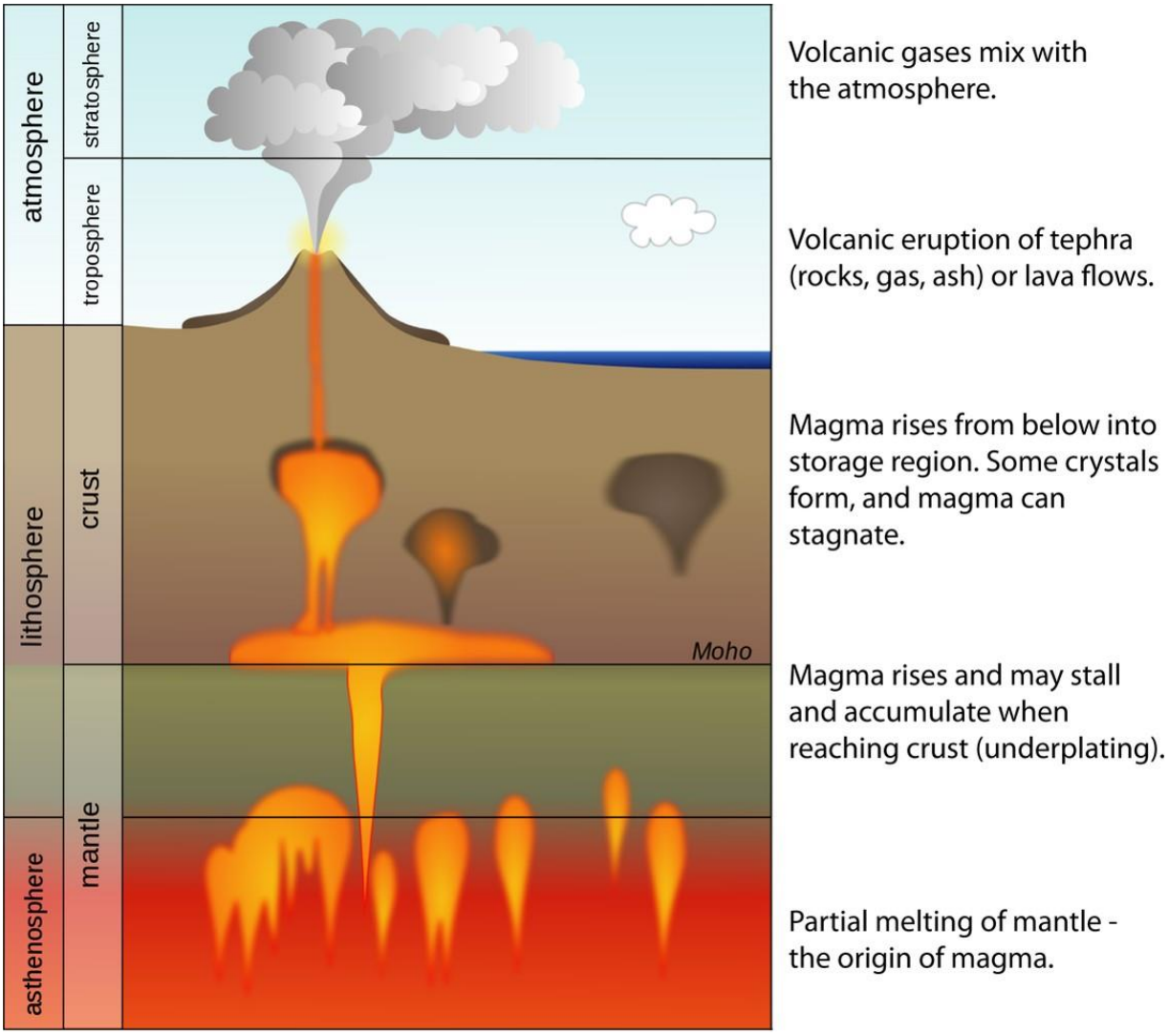


Figure 8.5: Illustration of the basic process of magma formation, movement to the surface, and eruption through a volcanic vent.

Attributions

- Figure 8.4: “Bowen’s Reaction Series and Associated Igneous Rocks” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 8.5: “Basic Process of Magma Formation” (Public Domain; based on an image from Woudloper via USGS)

Viscosity

Most of the minerals in igneous rocks are **silicate minerals**, and all the minerals shown in **Bowen's Reaction Series** belong to the silicate mineral group. All silicate minerals have crystal structures containing **silica tetrahedra**. These silica tetrahedra can be linked in a variety of ways, to form sheets, linked chains, or a 3-dimensional framework. The lower temperature minerals (quartz, muscovite and potassium feldspar) have more linked tetrahedra than the high temperature minerals (olivine, amphibole and pyroxene). Recall from our mineral unit how silica tetrahedra are linked to form the mineral **quartz**. What do you think will happen to the silica tetrahedra when quartz melts? The crystal structure is lost, the regularly repeated structure is gone, but the tetrahedral links are maintained (though distorted). The bonds that link these tetrahedra are strong, and magma temperatures are not high enough to break every bond. This means that felsic magmas in which quartz crystallizes will have a lot of these linked tetrahedra, whereas mafic magmas, which do not contain enough silica to crystallize quartz, will contain fewer linked tetrahedra. Why is the silica content, and specifically the amount of linked tetrahedra, so important? A large amount of linked silica tetrahedra will result in a magma or lava that is very viscous: it will not flow easily. **Viscosity** is a material's resistance to flow and is affected by the chemistry, temperature, and gas content of the melt.

Imagine sitting down to a breakfast (or brunch) of pancakes with syrup. Where do you store your syrup? In the refrigerator or pantry? Syrup stored in the refrigerator is cold and therefore pours slowly, whereas syrup stored in the pantry flows more easily. Consider what happens to the syrup when you heat it in the microwave; it will now flow even more readily. The syrup's viscosity, and the connections between the sugar crystals in the syrup, is affected by the temperature. Cold syrup has a higher viscosity, while hotter syrup has a lower viscosity. This is also true for molten rock: in general, melts that are hotter tend to flow more easily. These runny lavas also typically contain fewer linked silica tetrahedra, and readily allow gases to escape. Mafic lavas, sourced from the hotter mantle or oceanic crust and containing fewer silica chains, will flow faster than intermediate or felsic lavas. The viscosity difference between differently composed magmas affects the overall shape or appearance of the volcano, as well as the style of eruption (effusive vs. explosive).

Composition	Temperature	Gas content	Viscosity	Explosivity potential
Mafic Olivine, pyroxene, amphibole	High	Gases readily escape	Low (runny)	Low
Intermediate Amphibole, biotite, Na-rich plagioclase feldspar	Moderate	Gases become somewhat trapped	Moderate	Moderate
Felsic Quartz, muscovite, potassium feldspar	Low	Gases are trapped	High (sticky)	High

Table 8.1: Igneous rock compositions and their volcanic relationships.

Attributions

- Table 8.1: “Igneous Compositions” (CC-BY 4.0; Chloe Branciforte, own work)

Volcanic Materials

Lava Flows

Mafic lavas include pillow basalts, pahoehoe, and a'a lavas. **Pillow basalts** are the result of an underwater eruption. These pillow-shaped bodies, commonly erupted at mid-ocean ridges and oceanic hot-spots, form as a result of rapid cooling (**Figure 8.6**). The exterior of the pillow is commonly a volcanic glass, while the interior may be crystalline.

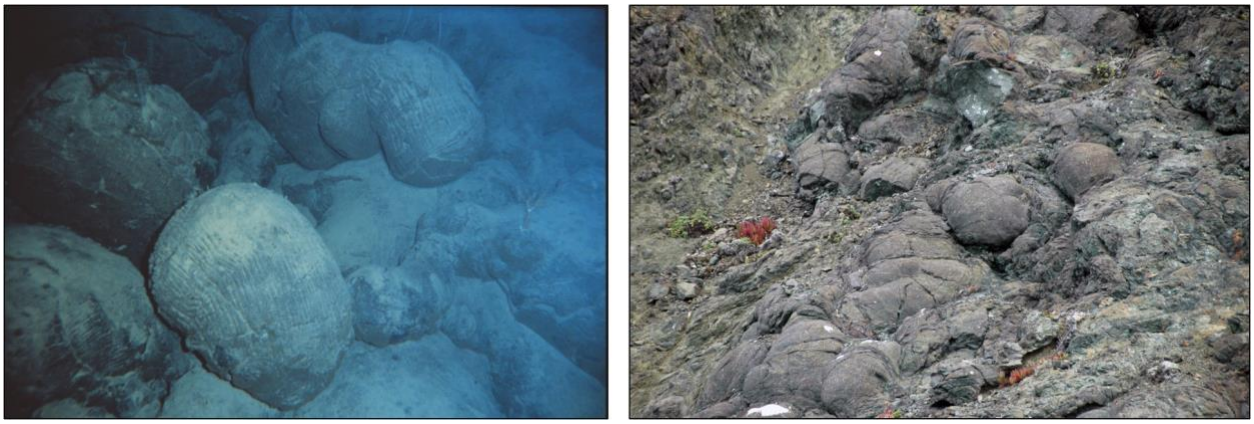


Figure 8.6: *Left:* Pillow lava rocks on the slope off Hawaii form when magma oozes from below. *Right:* The bulbous, rounded masses of volcanic rock seen here are pillow basalts from the Jurassic of California. The morphology is diagnostic of underwater lava eruptions. These rocks are part of the Franciscan Complex - they represent the top portion of Jurassic-aged oceanic crust. This basaltic crust originally formed at an ancient mid-ocean ridge and got plastered onto the edge of the North American continent along a now-inactive subduction zone. The upper portions of the subducting oceanic slab (the Farallon Plate) got scraped off to form an accretionary wedge. The basalts have been metamorphosed into greenstone, but much of the outcrop is still dark gray to black in color.

Pahoehoe lava flows have a very low viscosity and are typically runny with a smooth and lobate shape. When cooled, they form rope-like patterns (**Figure 8.7**). Due to their runny nature they are capable of moving great distances from their **volcanic vent**.

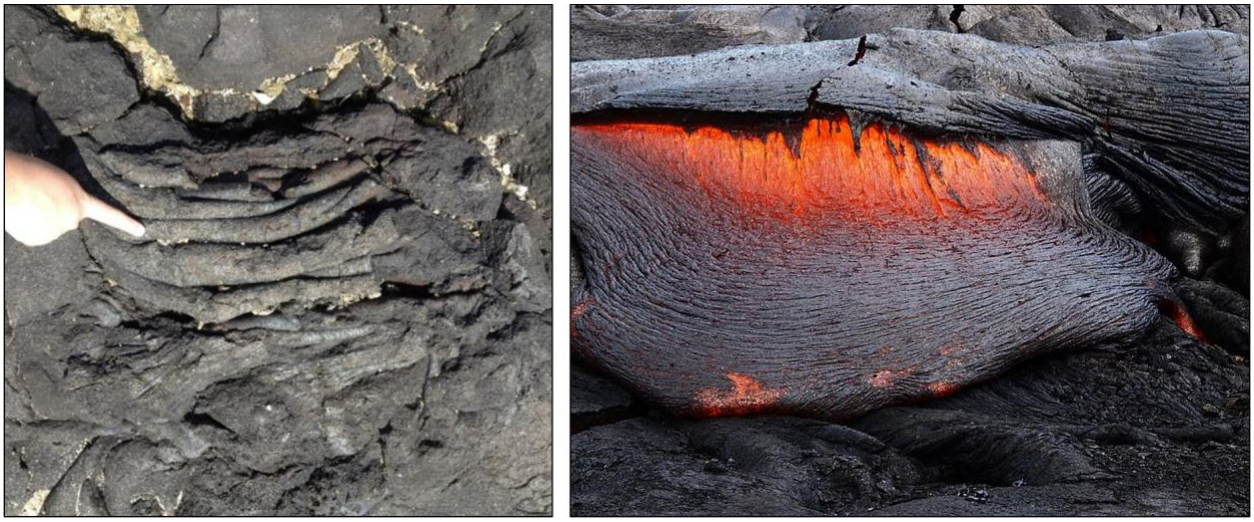


Figure 8.7: *Left:* Cooled pahoehoe lava near Kilauea on the Big Island of Hawaii. *Right:* Pahoehoe lava forming ropy lava at Kilauea volcano in Hawaii.

A'a lava flows run slightly cooler and therefore are a bit more viscous. This causes the lava surface to appear uneven and broken. When cooled, the rock remains jagged and rough (**Figure 8.8**). If you could choose to hike over a cooled pahoehoe or an a'a flow, the pahoehoe flow would be much kinder on your feet and ankles (and hiking boots!).

Figure 8.8: *Left:* Cooled a'a lava near Kilauea on the Big Island of Hawaii. *Right:* A slowly advancing a'a flow at the base of Kilauea volcano in Hawaii.

Intermediate to felsic lavas are typically referred to as **block lavas** or rhyolitic or dacite lavas. These lava flows are very viscous and are unable to move very far from their vent. These lavas can pile up on themselves and produce a mound or dome of lava (**Figure 8.9**).

Figure 8.9: Kanaga Volcano, located in the Aleutian Islands chain of Alaska; the foreground shows a lava flow from the 1906 eruption event.

Columnar Joints form when lava flows cool, solidify, and contract. Long vertical cracks, or **joints**, form within the brittle rock to allow for the shrinkage. Viewed from above, the joints form polygons with 5, 6, or 7- sides, and angles of approximately 120° between sides (**Figure 8.10**). Devil's Postpile National Monument here in California has amazing examples of these columnar joints. Watch this video for a virtual field trip to Devil's Postpile.

Figure 8.10: The columns of Devils Postpile in California were formed when lava cooled and cracked, creating hexagonal shapes.

Volcanic Gases

Magmas contain dissolved gases that expand as the magma migrates up through the crust. As the gases expand, bubbles form, much like the bubbles produced after you crack open a soda. These gases become an important driving factor behind eruptions. If the gas bubbles are able to be vented from the magma slowly, the eruption will be effusive, or gentle. Effusive eruptions typically produce lower viscosity lava flows and/or lava fountains, where the height of the lava fountain depends on the gas content of the lava. If the gas bubbles become trapped in the magma and cannot be vented to the surface, however, pressure begins to build. Eventually the pressure exceeds the strength of the rock, and the resulting eruption can be explosive and violent. Explosive eruptions are typical of more viscous magmas.

Common volcanic gases include water vapor, carbon dioxide, and sulfur dioxide, but, depending on the chemistry of the magma and host rock, other gases are possible. Certain volcanic gases can pose significant hazards to local populations, causing problems for health, crops, and to infrastructure. For more information about gases impacting a broader community, read this

USGS Fact Sheet: Invisible CO2 Gas Killing Trees at Mammoth Mountain, California or explore the 1986 disaster at Lake Nyos, Cameroon in Africa.

Figure 8.11: Collecting Gas Sample at a Fumarole. A USGS geologist Deborah Bergfeld is shown here collecting a gas sample from a superheated (hotter than the boiling point) fumarole in Little Hot Springs Valley at Lassen Volcanic National Park, California.

During the Precambrian, volcanic gases were a likely source of our early atmosphere and oceans. Gases emitted by volcanoes continue to influence the atmosphere, for example the Mt. Pinatubo eruption in 1991 released large quantities of sulfur dioxide that resulted in global cooling by 1°F. While this may not seem like a large number, a single degree globally can have serious ramifications on weather at a local level. While some volcanic eruptions have had a global impact on the climate, the total amount of volcanic outgassing during human history does not come close to measuring up to how rapidly humans are altering the composition of the atmosphere.

Pyroclastic Debris

Pyroclastic debris, **tephra**, or cinders are the fragmented volcanic material released during a volcanic eruption. Smaller sized material can travel great distances along air currents. Pyroclastic debris are classified according to their size.

Figure 8.12: A volcanologist next to a 6-meter-high block that was carried about 4 kilometers down the north flank of Augustine volcano in Alaska during the 1976 eruption.

Larger pieces (>2.5 inches in diameter) are referred to as volcanic blocks and bombs. **Volcanic blocks** are typically jagged shaped pieces dislodged from the volcano during an eruption (**Figure 8.12**).

Volcanic bombs are semi-molten or molten blebs of lava that get hurled through the air during an eruption. As they fly through the air, they begin to cool and harden. Smaller pieces can be completely solidified by the time they impact the ground, while larger pieces may still be partially molten upon impact and flatten on one side (**Figure 8.13**). Both volcanic blocks and bombs typically remain closer to their volcanic source, although if an eruption is very gas-rich and therefore explosive, they can be hurled miles away.

Figure 8.13: "Almond" volcanic bomb found in the Cinder Cones region of the Mojave National Preserve in San Bernardino County, California.

Lapilli, or **cinders,** are golf-ball to pea-sized vesicular or glassy pieces (**Figure 8.14**). These pieces can be carried upward within a volcanic plume and downwind in a volcanic cloud, but fall to the ground as the eruption cloud cools. These pieces can quickly pile up on roofs of structures, which can result in cave-ins.

Figure 8.14: Lapilli on Mt. Etna in Sicily

Volcanic ash is the smallest of the fragmented material. Volcanic ash is different from the ash of a fire. Wildfires, bonfires, or fireplace ash is created as a result of a chemical reaction with organic material. Volcanic ash is rock or glass particles generated during an explosive eruption (**Figure 8.15**). Volcanic ash can be so small it can pass through the weave of fabric, even denim. After an explosive eruption you may see people with bandanas or t-shirts covering their mouth and nose. The ash may be small enough to pass through this fabric, so, typically, medical grade masks (N-95 or better) are the best barrier for keeping the particulates out of your respiratory system. We will return to volcanic hazards in a later section.

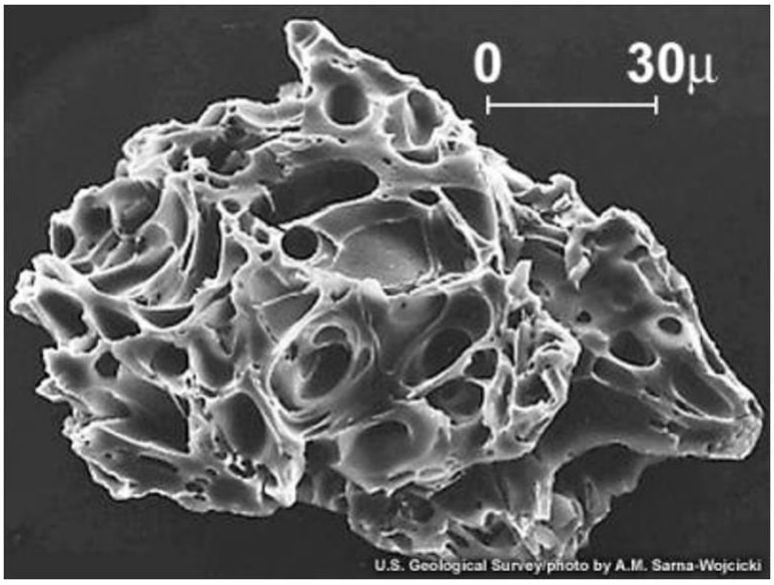


Figure 8.15: Highly vesicular glass ash shard from the May 18,1980 Mount St. Helens eruption, magnified 200 times in a scanning electron micrograph (SEM), measuring just over 0.1 mm.

Attributions

- Figure 8.6: Derivative of {“Pillow Lavas Off Hawaii” (Public Domain, NOAA via Wikimedia Commons and “Pillow Basalts” (CC-BY 2.0; James St. John via Flickr)} by Chloe Branciforte
- Figure 8.7: Derivative of {“Pahoehoe” (CC-BY 4.0, Chloe Branciforte, own work) and “Pahoehoe Lava Forming Ropy Lava” (CC-BY-SA 4.0; Rufiyaa via Wikimedia Commons)} by Chloe Branciforte
- Figure 8.8: Derivative of {“A’a Flow” (CC-BY 4.0, Chloe Branciforte, own work) and “A’a” (Public Domain; USGS HVO)} by Chloe Branciforte
- Figure 8.9: “Kanaga Volcano” (Public Domain; Michelle Combs/USGS via Flickr)
- Figure 8.10: “Devils Postpile” (Public Domain; NPS)
- Figure 8.11: “Collecting Gas Sample at a Fumarole” (Public Domain; Fred Murphy/USGS via Flickr)
- Figure 8.12: “GVP-02668” (Public Domain; Harry Glicken/USGS)
- Figure 8.13: "Volcanic Bomb" (Public Domain; Mark A. Wilson via Wikimedia Commons)
- Figure 8.14: “Etna-Lapilli” (CC-BY-SA 3.0; Ji-Elle via Wikimedia Commons)
- Figure 8.15: “Etna-Lapilli” (Public Domain; USGS)

Volcano Types

The size, shape, and eruptive style of any volcano ultimately depends on the magma composition and types of materials erupted. Mafic lava flows can travel quite far before solidifying completely. These lava flows can even form lava tubes, through which molten lava flows like a river under a cave-like crust of hardened lava rock. A **shield volcano** typically forms from mafic lava flows. Shield volcanoes are very broad at their base and have relatively gentle slopes. In map-view they look similar to Captain America's shield, hence their name. Shield volcanoes are the largest of the volcano types, although they are gentle giants.

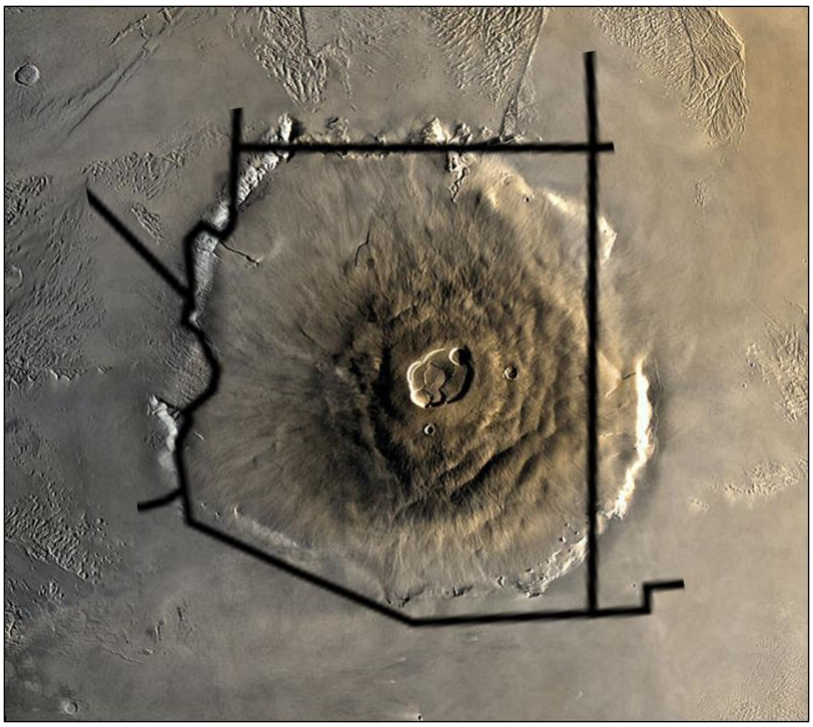


Figure 8.16: The largest known volcano in the solar system, Olympus Mons, is about the size of Arizona. Surrounding the volcano is an outward-facing scarp 550 km in diameter and several kilometers high. Beyond the scarp is a moat filled with lava, most likely derived from Olympus Mons.

One of the largest landforms and biggest volcano in our solar system is a shield volcano on Mars, Olympus Mons, which is roughly the size of Arizona (**Figure 8.16**). Shield volcanoes are frequently associated with mantle plumes, although some form at divergent boundaries, either on land or on the seafloor.

There are several locations around the world where large amounts of mafic basalt flows are found, without having formed a shield volcano. These places include the Deccan Traps in India, Siberian Traps in Russia, Central Atlantic Magmatic Province (CAMP), and the Columbia River Basalt Group of the US Pacific northwest. Such vast outpourings of mafic lava are called **flood basalts** or **large igneous provinces (LIPs)** and are believed to be caused by mantle plumes (hotspots) that partially melt the mantle beneath the Earth's crust. The mafic magma generated by such a mantle plume reaches Earth's surface through many fractures or fissures instead of one central vent and can output millions of square kilometers of lava over hundreds of thousands to millions of years.

A **cinder cone** (spatter cone) forms from cooler mafic lava released through a vent. The cooler lava traps gases, increasing the explosivity of the volcano and generating pyroclastic debris or cinders. The debris piles up around the vent, forming a small, conical shaped volcano (**Figure 8.17**). Typically, cinder cones are the smallest of the volcano styles. Most are made up of fragments of vesicular mafic rock (pumice or scoria). In many cases, these later became the sites of effusive lava flows after the gases have been vented from the magma. Most cinder cones are monogenetic, meaning that they formed during a single eruptive phase, lasting weeks to months. These cones are made almost entirely of loose fragments that have very little cohesion, allowing most to be quickly eroded away.

Figure 8.17: Amboy Crater, a cinder cone located in the eastern Mojave Desert of southern California.

A **composite volcano** (or stratovolcano) forms from intermediate to felsic magmas erupting through a central vent. This volcano type gets its name because it is a composite of lava flows and pyroclastic materials produced during explosive eruptions (**Figure 8.18**). Recall that it is common to have dissolved gases within magma and that some gases may escape from the magma while still underground; however, the most spectacular release of gases occurs during an explosive eruption. At many such volcanoes, magma is stored in a magma chamber in the upper part of the crust.

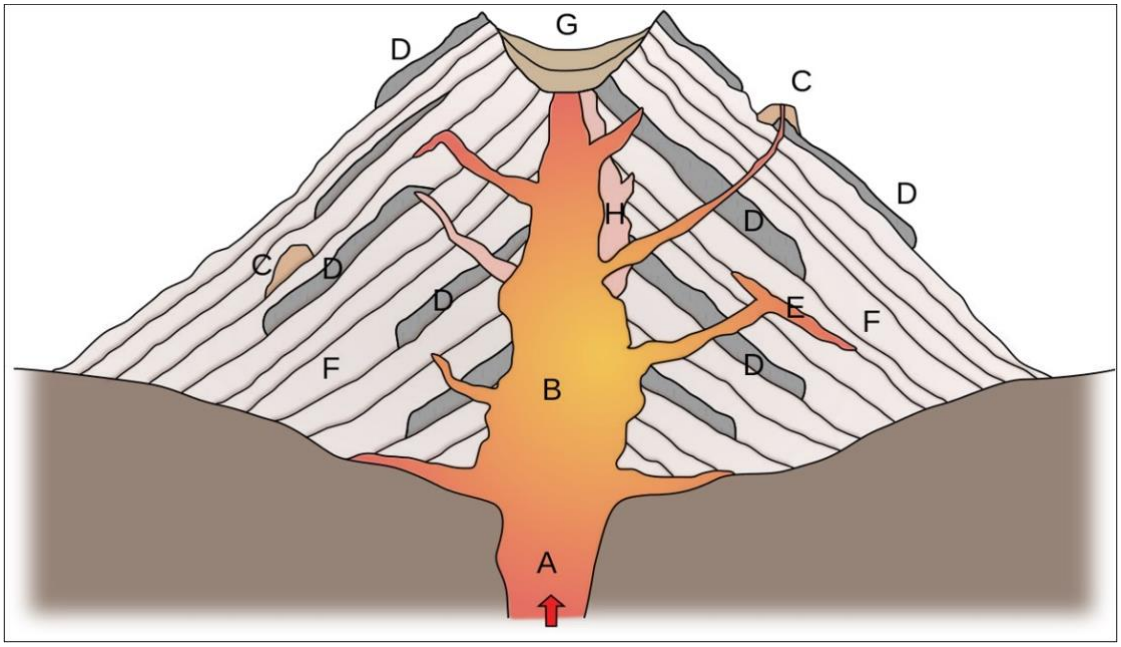


Figure 8.18: A cross-section through a stratovolcano (composite volcano), illustrating the physical build-up. A: inflow of magma through central vent; B: central vent; C: cone on the flank of the volcano; D: lava flow; E: sill; F: pyroclastic deposits; G: crater infill; H: old vent.

A **lava dome** is formed from viscous block lava that is resistant to flow, like thick toothpaste being squeezed from a tube. This lava plugs the **volcanic vent**, building up intense pressure; when the pressure exceeds the strength of the rock, the volcano rips apart in a violent eruption. Typically, **spines** grow out of lava domes and can indicate an upcoming eruption. Lava domes can exist on their own (Lassen Peak) or be associated with composite volcanoes (inside the crater of Mt. St. Helens). As a dome ages, its lavas evolve, becoming more silica rich and with a higher viscosity.

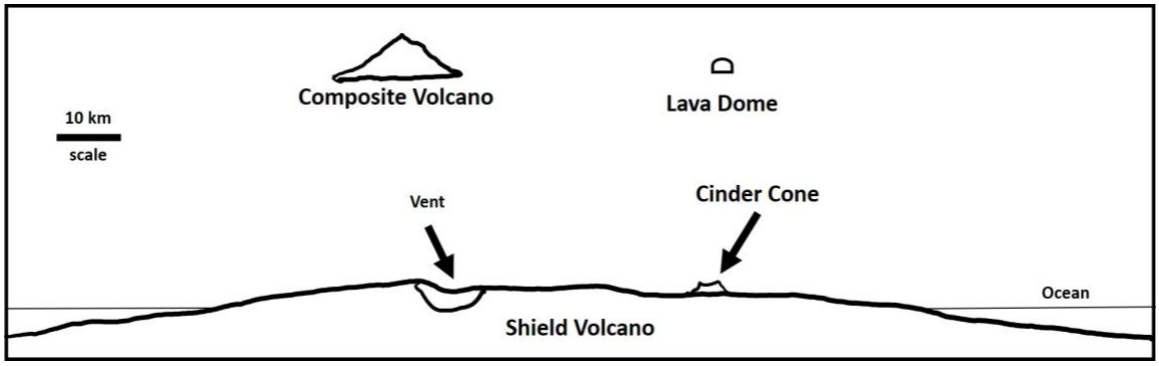


Figure 8.19: A comparison of a typical shield volcano versus the smaller cinder cone, steeply-sloped composite volcano, and lava dome. The size and shape of these volcano types are due to the different types of magma and associated eruption styles.

Volcano style	Size and shape	Eruption material	Composition	Viscosity & Explosivity	Common Tectonic Setting	Examples
Caldera	Broad depression with flat bottom and steep sides. Generally >1 mi in diameter	Mix; pyroclastics, lava flows	Intermediate to felsic (eruption style) Mafic (subsidence style)	High (eruption) Low to intermediate (subsidence)	Subduction zones, continental hot spots (eruption), divergent boundaries, oceanic hot spot (subsidence)	Long Valley, CA Yellowstone, WY (eruption) Kilauea, HI Bardarbunga, Iceland (subsidence)
Shield	Large, broad shape (up to 125 mi across); not steep (slopes 2-10°)	Lava flows	Mafic	Low	Divergent boundaries; oceanic hot spots	Hawaiian Islands Iceland
Cinder (scoria) cone	Small size (30 to 350 ft); steep (slopes >20°)	Pyroclastic debris	Mafic	Low to intermediate	Varies; common on the flanks of other volcanoes	Cinder Cone, CA Amboy Crater, CA
Composite cone (strato-volcano)	Medium size (1000's of ft high); moderate steepness (10-30°)	Mix; pyroclastics, lava flows	Intermediate to felsic	Intermediate to high	Subduction zones	Mt. Shasta, CA Mt. St. Helens, WA Mt. Fuji, Japan
Lava dome (rhyolite dome)	Small size	Block lavas	Felsic	High	Subduction zones, continental hot spots	Lassen Peak, CA Panum Crater, CA Sutter Buttes, CA

Table 8.2: A comparison of volcano types.

Hot spots are volcanically active areas on the Earth's surface that are likely a result of a **mantle plume** that rises from deep in the mantle toward the surface, resulting in melted rocks and volcanoes. These mantle plumes originate deep within Earth and are unaffected by the movement of the continents or the crust under the ocean. Mantle plumes appear to be stationary through time, but as the tectonic plate moves over the hot spot, a series of volcanoes are produced. There are a number of hot spots in the US, including under Hawaii and Yellowstone. Here in California, we have a hot spot situated beneath the Mammoth/Mono Lake region, an area home to Long Valley Caldera, which is heavily monitored by the California Volcano Observatory (CalVO).

Can You Dig It?

The Yellowstone Hotspot: *A hot spot beneath the North American plate is responsible for much of the geology in Yellowstone National Park in Wyoming. This park does not contain the typical volcanic features, as there is no conical shaped volcano. Instead much of the park sits within a series of three massive **calderas**; the largest is more than 30 miles across! During the last 2 million years, this hot spot has experienced three violent and explosive eruptions, with minor, less explosive eruptions in between. Partial melting of the overlying continental crust occurs as magma pools on the underside. The resulting magma has a high silica and gas content, which produces explosive eruptions like those identified by thick pyroclastic deposits in the geologic record. Want to learn more? Visit the Yellowstone NPS page.*

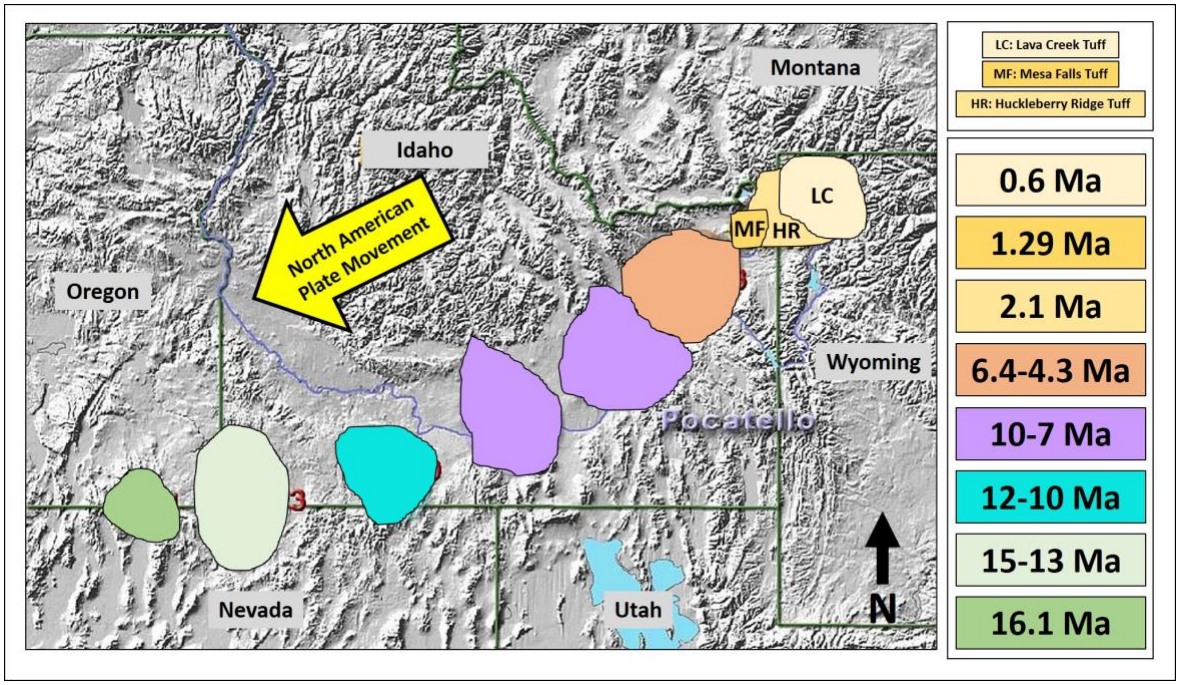


Figure 8.20: The Yellowstone Hot Spot track.

Attributions

- Figure 8.16: Derivative of “Olympus Mons” (Public Domain; NASA) by Chloe Branciforte
- Figure 8.17: “Amboy Crater” (Public Domain; Bob Wick/BLM via Fickr)
- Figure 8.18: “Stratovolcano Cross-section” (CC-BY-SA 3.0; Woudloper via Wikimedia Commons)
- Figure 8.19: “Volcano Sizes” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 8.2: “Volcano Types” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 8.20: Derivative of “Yellowstone Hot Spot Track” (CC-BY 3.0; Kelvin Case/NPS via Wikimedia Commons) by Chloe Branciforte

Eruption Styles

There are four types of eruptions with properties determined mostly by the silica and gas contents of magma. In order of increasing explosiveness, these are **Hawaiian**, **Strombolian**, **Vulcanian**, and **Plinian** eruptions. Any composition of magma can have an explosive eruption if the magma suddenly encounters water. Hot magma contacting groundwater or seawater causes the water to flash to steam. Explosive eruptions driven by water are called **hydrovolcanic (or phreatic) eruptions**.

Hawaiian eruptions are named after the characteristic eruptions of the volcanoes of the Hawaiian Islands. Hawaiian eruptions are effusive (flowing) rather than explosive because they erupt low-viscosity mafic lava. Hawaiian eruptions form shield volcanoes and can also take the form of fissure eruptions. Fissure eruptions occur when lava erupts from long cracks in the ground rather than from a central vent.

Strombolian eruptions, named for Mt. Stromboli in Italy, occur when mafic lava has higher viscosity and higher gas content. The sticky lava is ejected in loud, violent, but short-lived spattery eruptions. Clumps of gas-rich lava are thrown tens to hundreds of feet in the air and accumulate as scoria in a pile around the vent, forming cinder cones.

Vulcanian eruptions get their name from the volcanic Italian island of Vulcano, which itself takes the name of the Roman god of fire, Vulcan. In Roman mythology, Vulcan was the maker of armor and weaponry for the gods, and volcanic eruptions were attributed to him working in his forge. Vulcanian eruptions are far more explosive than Strombolian eruptions, and can blast tephra and gas to a height of 3 to 6 miles. The explosiveness is related to a build-up of pressure as the higher viscosity of intermediate silica content lava restricts the escape of gas. Vulcanian eruptions produce large quantities of ash, in addition to blocks and bombs.

Plinian eruptions are explosive eruptions of intermediate to felsic lava and can form eruptive columns up to 30 miles high. The origin of the name is the eruption of Vesuvius in 79 CE, which buried the towns of Pompeii and Herculaneum. The Roman admiral Gaius Plinius Secundus, also known as Pliny the Elder, attempted a rescue mission when he saw the column of ash and debris above Vesuvius, but died of unknown causes before he was able to reach Herculaneum.

Hydrovolcanic (phreatic) eruptions can be far more explosive than Plinian eruptions. They occur when water - in the form of groundwater, seawater, or even melting glacial ice or snow - comes into contact with magma. Heat from the magma abruptly changes water to steam, which

can expand to more than a thousand times the original volume of water. This sudden expansion results in an explosive force that can blast a volcano to pieces and create large amounts of volcanic ash.

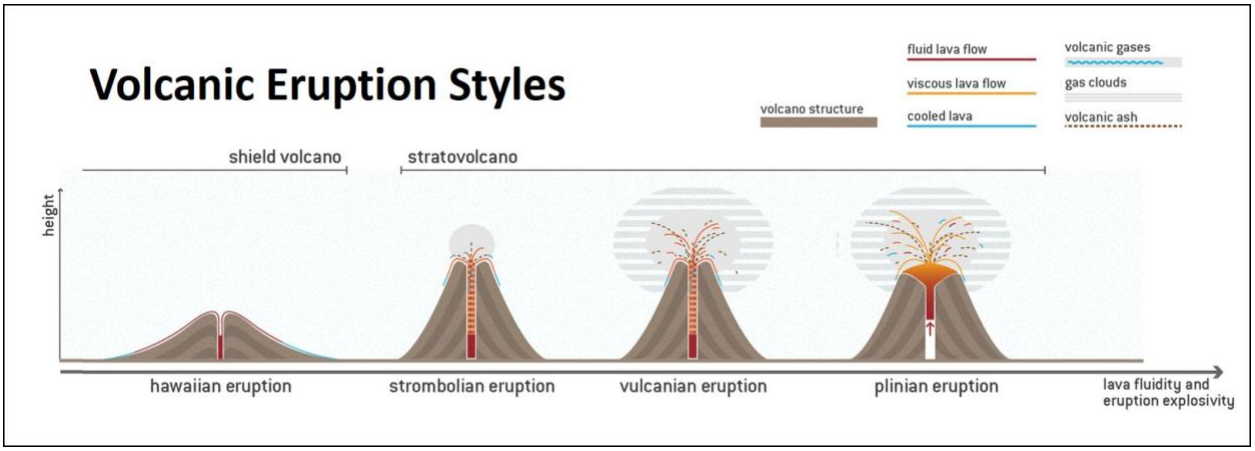


Figure 8.21: Gas content is the primary driver of eruptions. High viscosity and gas content is typical of composite cones, which can produce Plinian (and ultra-Plinian) eruptions. These eruptions produce large, tall plume clouds, with gases and ash content reaching the stratosphere.

Attributions

- Figure 8.21: Derivative of “Types of Volcanoes and Eruption Features” (CC-BY-SA 4.0; Chiara Cingottini, DensityDesign Research Lab via Wikimedia Commons) by Chloe Branciforte

Volcanic Explosivity Index (VEI)

To determine the explosivity value of an eruption, geologists will calculate the volume of eruption products, measure the height of the eruption column, and make qualitative observations about the eruption impact.

This scale is logarithmic, with each interval on the scale representing a tenfold increase in observed ejecta criteria (except between VEI 0, VEI 1 and VEI 2). A value of 0 is given for non-explosive eruptions, defined as less than 10,000 m^3 (350,000 cu ft) of tephra ejected. The largest volcanic eruptions in history, supereruptions, are given a magnitude of 8, representing a mega-colossal explosive eruption that can eject more than 1000 km^3 (>240 cubic miles) of tephra and have a cloud column height of over 20 km (12 mi).

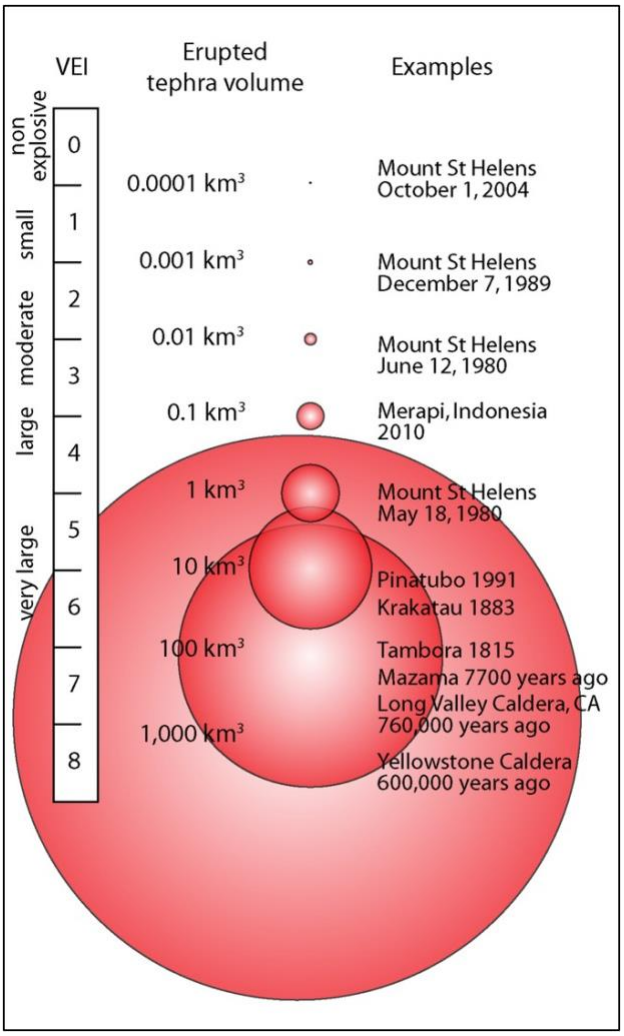


Figure 8.22: Volume of products, eruption cloud height, and qualitative observations (using terms ranging from "gentle" to "mega-colossal") are used to determine the explosivity value.

Attributions

- Figure 8.22: “Volcanic Explosivity Index (VEI)” (Public Domain; USGS)

Volcanic Hazards

While shield volcanoes are more massive, they are far less dangerous to a population than the smaller composite volcanoes. Shield volcanoes produce runny lavas that may fountain at a vent, but usually end up flowing passively down the flanks of the volcano. While property damage may be significant (see the 2018 Kilauea eruption), anyone living on or near a shield volcano is not likely to perish due to the lava flows. This is not the case for the explosive eruptions of composite volcanoes that are associated with many distinct volcanic hazards (**Figure 8.22**). These eruptions produce a lot of pyroclastic debris, that range in size from microscopic ash to huge volcanic blocks. These pyroclastic debris first travel high up into the atmosphere as an eruption column, which spreads outward with the prevailing wind direction. As the eruption widens the central vent, the eruption column decreases its upward momentum. As a result, the pyroclastic material collapses down the flanks of the volcano as a **pyroclastic flow**: a very dangerous, fast moving, mixture of hot volcanic material and noxious gases.

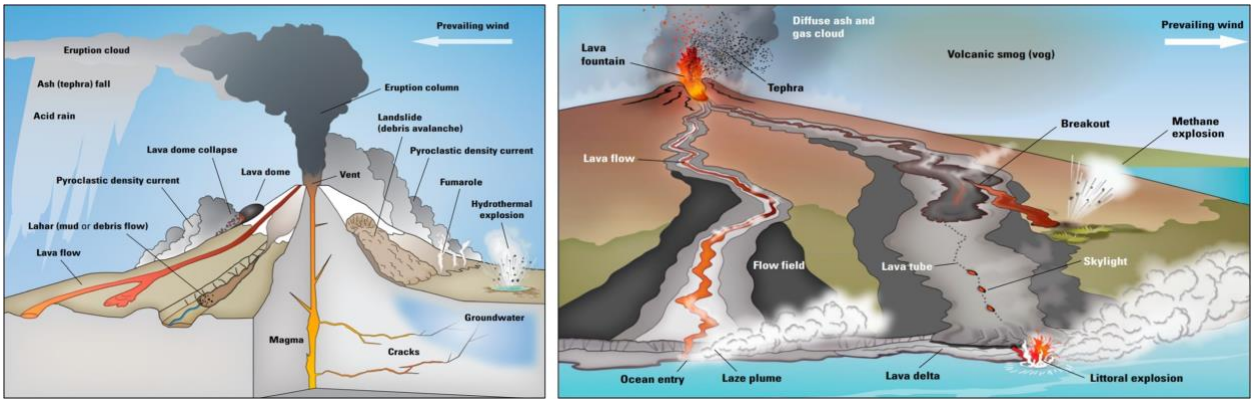


Figure 8.23: Hazards and other features associated with composite and shield volcanoes.

Many composite volcanoes are capped by snow and ice, and even a small eruption can result in meltwater running down the sides of the volcano, which creates volcanic mudflows or **lahars**. The meltwater easily erodes the ash and other volcanic debris on the flanks of the volcano and results in a fast-moving slurry of mud and larger material such as trees and boulders. Lahars move swiftly through river channels and can endanger any town or city that is built in the low-lying areas downstream from the volcano. Lahars can also be generated by large amounts of rainfall in the area. In general, lahars are uncommon in the Lassen Peak region of northern California; however, there are a few deposits found in drainages, demonstrating that these valleys are susceptible to future lahars. In the Cascade region of Washington and Oregon, there are several ancient volcanic mudflow deposits recognized. Many of the communities in the Pacific northwest have lahar monitoring systems available to detect these mudflows.

Volcanoes can be monitored in a variety of ways, including via seismic activity (earthquakes), changes in slope, gas emissions, thermal imagery, and more (**Figure 8.23**). By combining information from these 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.

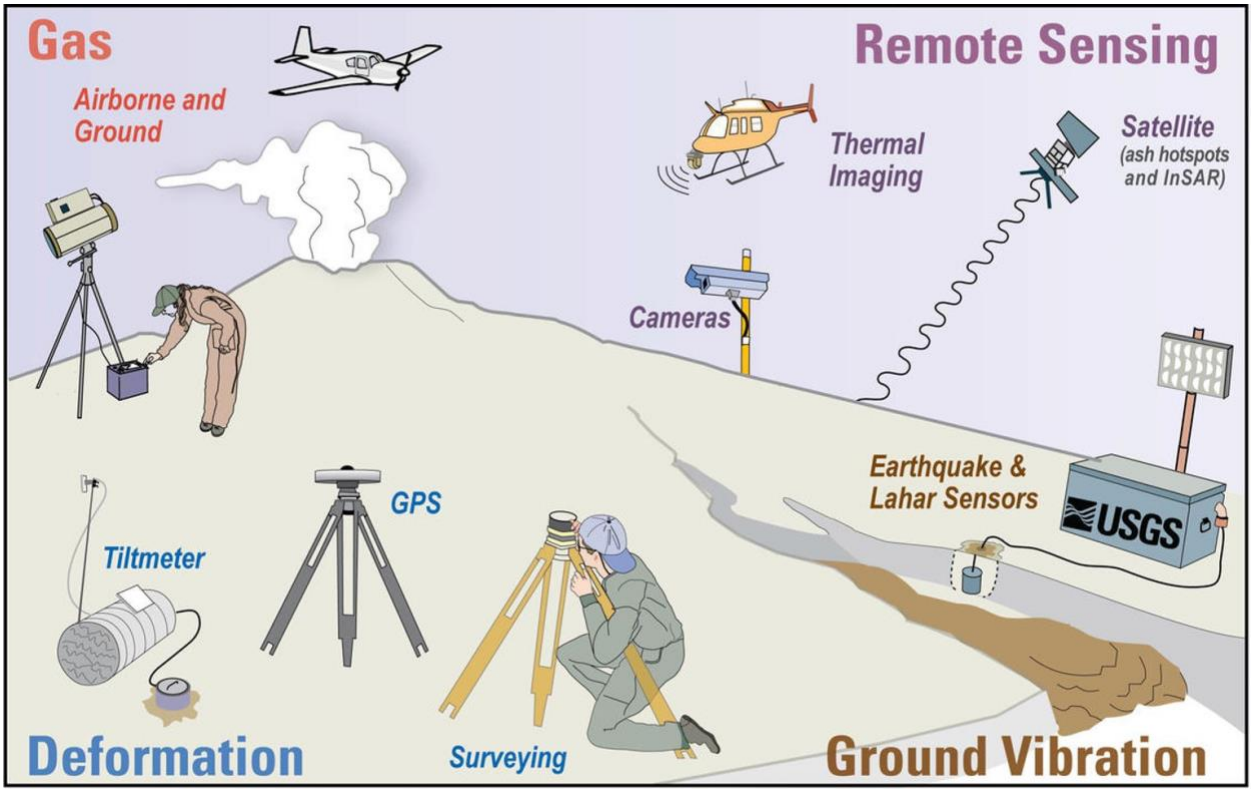


Figure 8.24: Volcanic monitoring types and methods employed by the USGS Volcano Hazards Program.

Attributions

- Figure 8.23: Derivative of “Living with Volcano Hazards” (Public Domain; Lisa M. Faust and Bobbie Myers, USGS) by Chloe Branciforte
- Figure 8.24: “Volcanic Monitoring Types and Methods Employed by the USGS” (Public Domain; Lisa M. Faust, USGS)

Activity 8A: Concept Sketches and Volcanoes

A **concept sketch** is a simplified drawing illustrating the main aspects of landscape or system. It is annotated with concise but complete labels that identify important features. Short sentences describe the processes that are occurring. The final aim is to show the relationships between features and processes. It is not simply a sketch labeled with only the names of features. See a rubric below for what is expected for each success level. Point values will be determined by your instructor.

Skill	Emerging	Progressing	Partial Mastery	Mastery
Identify **Features**	Incomplete labeling.	Some labeling.	Most clearly labeled.	Relevant features clearly labeled.
Identify **Processes**	Incomplete identification and description.	Incomplete identification or description.	Clear identification and description.	Relevant processes clearly identified and described.
Explain **the Connections and Relationships Between Features/Processes**	Incomplete connections/relationships.	Suggests some connections/relationship.	Most connections/relationships highlighted effectively.	Relevant connections/relationships highlighted effectively.
Demonstrate **Proper Use of Terminology**	Incomplete or inappropriate use of terminology/units. Frequent errors and misunderstanding of the subject.	Attempts use of appropriate terminology/units. Some errors and missing components.	Consistent use of appropriate terminology/units. Few errors or missing components.	Consistent and successful use of appropriate terminology/units.
Assess **Scientific Accuracy**	Lacks organization with frequent errors, demonstrating misunderstanding of the subject.	Drawings are readable, with occasional oversimplifications, errors and/or missing components.	Drawings are readable. Consistent use of symbology and/or colors/patterns to illustrate major features and/or processes.	Drawings are clearly readable with accurate details illustrated through appropriate symbols and/or colors/patterns. Sketch shows a scale.

Table 5.3: Rubric for geology concept sketches.

More on Concept Maps is available via NAGT/SERC, Teach the Earth.

1. Draw a concept sketch of the volcano types. Labels should be short sentences explaining the relationships between geologic features and processes.

Attributions

- **Table 5.3: “Concept Sketch Rubric” (CC-BY 4.0; Chloe Branciforte and Emily Haddad, own work)**

Activity 8B: Magma Generation and Plate Tectonics

The following exercises use the browser version of Google Earth. For each question (or set of questions) paste the given location into the "Search" box. When searching your locations in Google Earth, be sure to zoom out to higher eye elevations in order to see all the important features of each area.

1. Type 19 53 48.36 N 155 34 58.11 W in the search bar of Google Earth and zoom out to an eye altitude of ~650 miles. Examine this location. Which of the following tectonic features does this island represent?

    a. Subduction
    b. Divergence or rifting
    c. Hot spot

2. How can you tell?

3. The melt that formed these volcanic islands was generated by which process?

    a. the decrease of pressure, or decompression melting
    b. the addition of volatiles, commonly water
    c. the increase of temperature only

4. Type 41 24 38.38 N 122 11 42.58 W in the search bar on Google Earth and zoom out to an eye altitude of ~530 miles. Consider this location. Which of the following tectonic features does this volcano represent?

    a. Subduction
    b. Divergence or rifting
    c. Hot spot

5. How can you tell?

6. The magma responsible for this volcano was generated by what process?

    a. the decrease of pressure, or decompression melting, and the addition of heat
    b. the addition of volatiles, commonly water, and the addition of heat
    c. the increase of temperature only

7. Type **San Andreas Fault** into the search bar on Google Earth. Can you locate any volcanoes along the trace of the fault? Why or why not?

Activity 8C: Association of Magma Type with Tectonic Setting

The questions in this exercise demonstrate the control that tectonic setting has on the type of magma produced. For the Google Earth questions copy and paste (or type in) the latitude and longitude coordinates into the search bar.

1. At Mid-Ocean Ridges (MORs), where oceanic plates are diverging, melt is generated by decompression and which causes partial melting of the mantle. What is the final composition of the melt produced here? *Hint: think about the rock type that makes up the oceanic crust.*

    a. ultramafic
    b. mafic
    c. intermediate
    d. felsic

2. Type 19°28'19.7"N 155°35'31.9"W in the search bar on Google Earth and zoom out to an eye altitude of ~110 miles. This volcano is composed of:

    a. mafic rocks because a hotspot partially melted the mantle below the oceanic crust
    b. mafic rocks because a hotspot partially melted the oceanic crust
    c. ultramafic rocks because a hotspot partially melted the mantle below the oceanic crust
    d. ultramafic rocks because a hotspot partially melted the oceanic crust

3. Type 41°24'38.4"N 122°11'42.6"W in the search bar in Google Earth. This volcano formed from an intermediate magma type, because:

    a. subduction of oceanic crust beneath the continental crust occurs here
    b. continental crust is subducting, causing magma to form
    c. a hot spot is partial melting the continental crust
    d. this is the result of a divergent plate boundary

4. Type 36°40'41.6"N 108°50'17.2"W in the search bar in Google Earth. The dark colored rock that forms a straight line on the surface is most likely:

    a. a pluton of ultramafic rock
    b. a dike of ultramafic rock
    c. a sill of mafic rock
    d. a dike of mafic rock

5. Type 37°44'39.19"N 119°31'59.05"W into the search bar in Google Earth and zoom out to an eye altitude of ~100 miles. The lighter colored rock that forms much of this area is most likely:

- **a.** a batholith of mafic rock
- **b.** a sill of mafic rock
- **c.** a batholith of felsic rock
- **d.** a sill of felsic rock

Activity 8D: Magma Viscosity

The following questions address what factors control how fast a melt can flow. The viscosity, a material's resistance to flow, depends primarily on the melt composition, but can also be affected by temperature and gas release.

1. Intermediate lavas can flow ??? than mafic lavas, due to the ??? viscosity.

- **a.** slower, higher
- **b.** slower, lower
- **c.** faster, higher
- **d.** faster, lower

2. Consider (or actually try) the following, if we compare how honey (or dark corn syrup) and water flow when poured from a container,

- **a.** then the honey (corn syrup) represents felsic magma, and the water represents mafic magma.
- **b.** then the honey (corn syrup) represents mafic magma, and the water represents mafic magma.

3. Imagine putting the honey (corn syrup) in the refrigerator overnight; will its viscosity be affected?

- **a.** yes, the viscosity will increase
- **b.** yes, the viscosity will decrease
- **c.** no, there will be no change as the composition stays the same

4. Keep the honey (corn syrup) in mind while you answer this question. When first erupted, basaltic lava typically erupts at around 2100°F. After flowing away from the vent, the temperature falls. How will the viscosity change as the lava flows away from the vent?

- **a.** Viscosity will increase.
- **b.** Viscosity will decrease.
- **c.** Viscosity will stay the same.

Activity 8E: Volcanic Landforms

The composition of a melt may also control what type of volcanic features or landforms are seen on the Earth's surface. In this exercise, you will use the browser version of Google Earth to identify these landforms. Copy and paste (or type in) the latitude and longitude coordinates into the search bar.

1. Type 43°25'04.2"N 113°31'37.4"W in the search bar of Google Earth. Zoom out to an eye elevation of ~170 miles. Notice the dark colored sparsely vegetated region. Based on the size and location of this volcanic feature, it is likely,
    - **a.** a basaltic dike
    - **b.** a shield volcano
    - **c.** a lava dome
    - **d.** a flood basalt

2. How can you tell?

3. More information on an area is always helpful. Zoom in to an eye elevation of 15 miles. Engage the Photos layer. Click on a few of the nearby photo icons to view pictures of the area as seen from the ground. Based on the images, this feature is likely,
    - **a.** a basalt flow
    - **b.** a felsic dome
    - **c.** a plutonic rock
    - **d.** an ultramafic rock

4. How can you tell?

5. Type 46°12'07.8"N 121°31'02.9"W in the search bar of Google Earth. This volcano (Mt. Adams) has a lot of snow cover and small glaciers on it, but you can still see the volcanic rock, especially on the eastern flank (side) of the volcano. Zoom in to an eye altitude of ~9000ft to closely examine the rocks on the eastern side of the volcano. This volcano is likely:
    - **a.** a shield volcano
    - **b.** a lava dome
    - **c.** a composite volcano
    - **d.** a cinder cone

6. How can you tell?

7. Type in 37°55'46.2"N 119°02'43.8"W in the search bar of Google Earth. Examine the shape of this feature by zooming in to an eye altitude of ~2000 ft; use the eye icon in the upper right corner to rotate the view. Now zoom out to an eye altitude of ~6500 ft to see the entire structure and the surrounding area. Based on the size and appearance of this volcanic feature, this is a:

- **a.** cinder cone
- **b.** shield volcano
- **c.** lava dome
- **d.** composite volcano

8. How can you tell?

9. Type in 34°32'41.5"N 115°47'26.1"W in the search bar of Google Earth. Examine the shape of this feature by zooming in to an eye altitude of ~2500 ft; use the eye icon in the upper right corner to rotate the view. Based on the size and appearance of this volcanic feature, this is a:

- **a.** shield volcano
- **b.** composite volcano
- **c.** lava dome
- **d.** cinder cone

10. How can you tell?

Activity 8F: Volcanic Hazards

Potential hazards associated with certain volcanic types can be identified using topographic maps or aerial photographs. In this exercise, use Google Earth and type in the locations into the search bar.

1. Type Mount St. Helens, WA in the search bar in Google Earth and examine the crater and surrounding area, at an eye altitude of ~25,000 ft. What do you notice about the appearance of the crater?

2. Using the measure tool, approximately how large is the gap in the crater wall?
    a. in meters:
    b. in feet:

3. Find the highest elevation you can along the crater rim. *Hint - the elevation will appear in the bottom right-hand corner. Hover your mouse anywhere on the screen to see the elevation.*
    a. In feet, approximately:

4. Find the lowest elevation you can around the volcano. *Hint - the elevation will appear in the bottom right-hand corner. Hover your mouse anywhere on the screen to see the elevation.*
    a. In feet, approximately:

5. Ensure your view is in 2D (click on the 3D in the bottom right corner and it will switch back). Fly around the volcano. What is the overall shape?

6. What type of volcano is Mt. St. Helens?

7. Zoom out so that you can see the coastline and Mt. St. Helens. What type of plate boundary is forming Mt. St. Helens?

8. How can you tell?

9. Based on the information you collected above what likely caused the odd form in the crater:
    a. a lahar removed the north side of the volcano
    b. a pyroclastic eruption removed the north side of the volcano
    c. a lava dome grew so large that it is higher than the north side of the crater
    d. a glacier has eroded the north side of the crater

10. Type Mount Rainier, WA in the search bar in Google Earth. Zoom out to an eye altitude of ~11 miles. Notice the spindly, arm-like features that surround the volcano. Which volcanic hazard do you think produced these features?
    a. Ash fall
    b. lahars
    c. Pyroclastic flows
    d. Lava flows

11. How can you tell?

12. Visit the Smithsonian Volcanism Program, a wonderful site, that puts over 10,000 years of volcanic eruptions at your fingertips. Search for volcanoes in the US from their database, scroll through the results to see the over 1100 volcanoes! Your instructor may have a specific volcano for you to look for, however if not, go ahead and select a volcano from a state other than California. Most of the volcanoes have a significant amount of information, however if you choose one without much data, select a new volcano. Familiarize yourself with the many tabs and facts regarding your volcano or volcanic system and answer the following,

    a. Where is the volcano located (provide a state or territory):

    b. What is the primary volcano type?

    c. What processes are producing magma here?

    d. Is there a date associated with the last eruption? If yes, indicate the date here:

    e. If available, what is the population density nearby?

13. Visit the Smithsonian Volcanism Program, a wonderful site, that puts over 10,000 years of volcanic eruptions at your fingertips. Search for volcanoes in the US from their database, scroll through the results to see the over 1100 volcanoes! Your instructor may have a specific volcano for you to look for, however if not, go ahead and select a volcano from California. Most of the volcanoes have a significant amount of information, however if you select one without information, select a new volcano. Familiarize yourself with the many tabs and facts regarding your volcano or volcanic system and answer the following,

a. What is the primary volcano type?

b. What processes are producing magma here? Explain your answer. *Hint - think about the overall tectonic location. It may be helpful to also locate your volcano in Google Earth to see where you are geographically.*

c. Is there a date associated with the last eruption? If yes, indicate the date here:

d. Locate your volcano selection in Google Earth. What is the closest community (city, town, etc.)?

e. How far is this community from the volcano?

f. What is the population of this community?

Activity 8G: Volcanic Materials

1. Identify the pyroclastic materials in **Figure 8.25**.

A:

B:

C:

A B C

Figure 8.25: Pyroclastic debris to categorize and identify for Activity 8G.

2. Identify the mafic lava flow types in **Figure 8.26**.

A:

B:

A B

Figure 8.26: Mafic lava flows to identify for Activity 8G.

Attributions

- Figure 8.25: Derivative of “Volcanic Tephra” (CC-BY 4.0; Chloe Branciforte, own work) and “Volcanic Bomb” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte
- Figure 8.26: Derivative of “Mafic Lava Flows” (CC-BY 2.0; James St. John via Flickr, Left and Right) by Chloe Branciforte

Chapter 9: Surface Water Processes

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Know the different stream drainage patterns and understand what they indicate about the underlying rock.
- ✔ Understand how streams erode, transport, and deposit sediment.
- ✔ Identify river landforms.
- ✔ Explain recurrence intervals and apply them towards flooding events.

Thumbnail for Chapter 9:

Thumbnail: "Mountain Majesty" (CC-BY 2.0; Angela Sevin via Wikimedia Commons)

The Water Cycle

How many times a day do you take water for granted? Do you assume the tap will be flowing when you turn on your faucet? That the shower will turn on, the toilet will flush, and you'll have water to cook your meals? Not only is water necessary for many of life's functions, it is also a considerable geologic agent. Water can sculpt the landscape dramatically over time, by both carving canyons and depositing thick layers of sediment. Some of these processes are slow and result in landscapes worn down over time; others, such as floods, can be dramatically fast and dangerous.

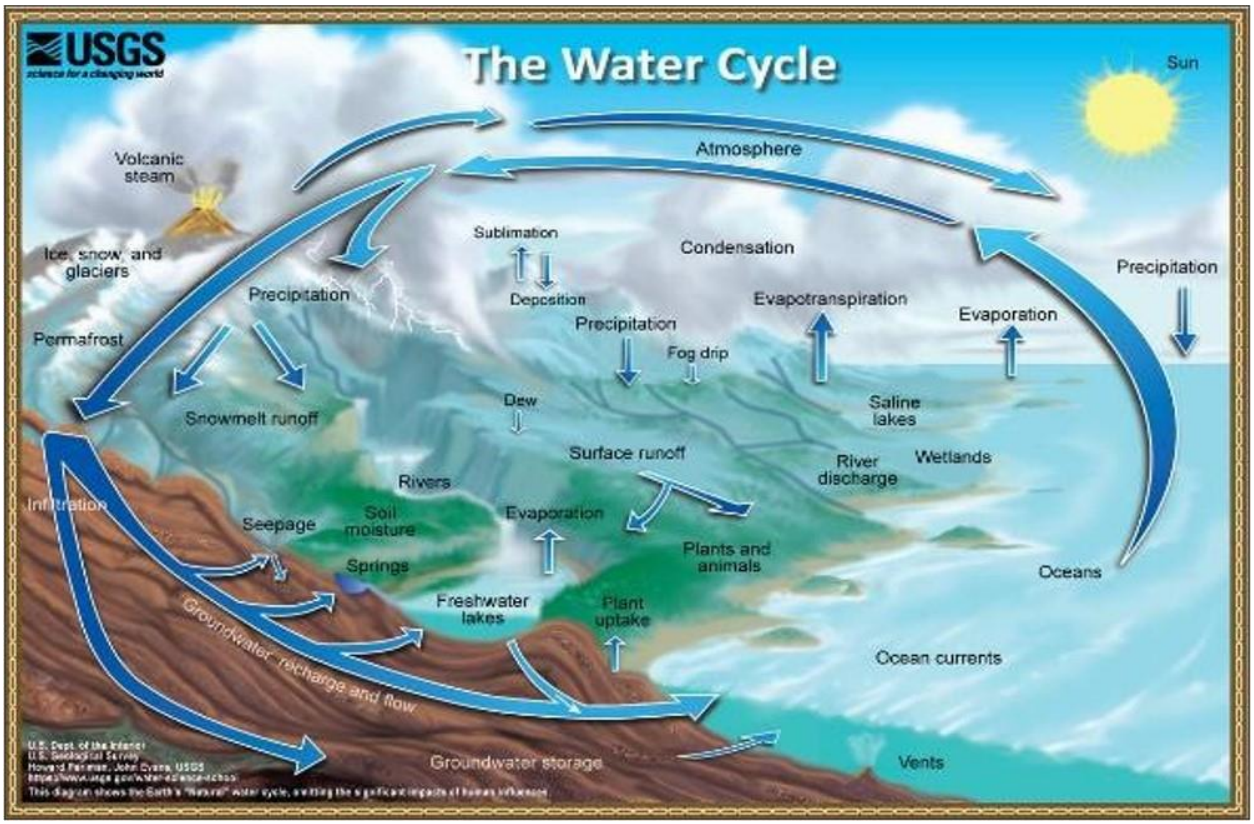


Figure 9.1: Earth's water is always in movement, and the natural water cycle (hydrologic cycle), describes the continuous movement of water on, above, and below the surface of the Earth. Water is always changing states between liquid, vapor, and ice, with these processes happening in the blink of an eye and over millions of years.

What happens to water during a rainstorm? Imagine that you are outside in a parking lot with grassy areas nearby. Where does the water from the parking lot go? Much of it will flow across the surface and eventually join a stream. What happens to the rain in the grassy area? Much of it will infiltrate, or soak into the ground. Water is continually recycled through the atmosphere, to the land, and back to the oceans. This movement of water through the Earth System is

referred to as the **hydrologic (water) cycle** (**Figure 9.1**). At Earth's surface, this cycle, powered by the sun, operates easily since water can change form from liquid to gas (or water vapor) quickly. The majority of water is found in oceans, but freshwater can be found in lakes, rivers and trapped away in glaciers and ice sheets. Additional water resources are also found in the ground, and will be discussed in another chapter (**Figure 9.2**).

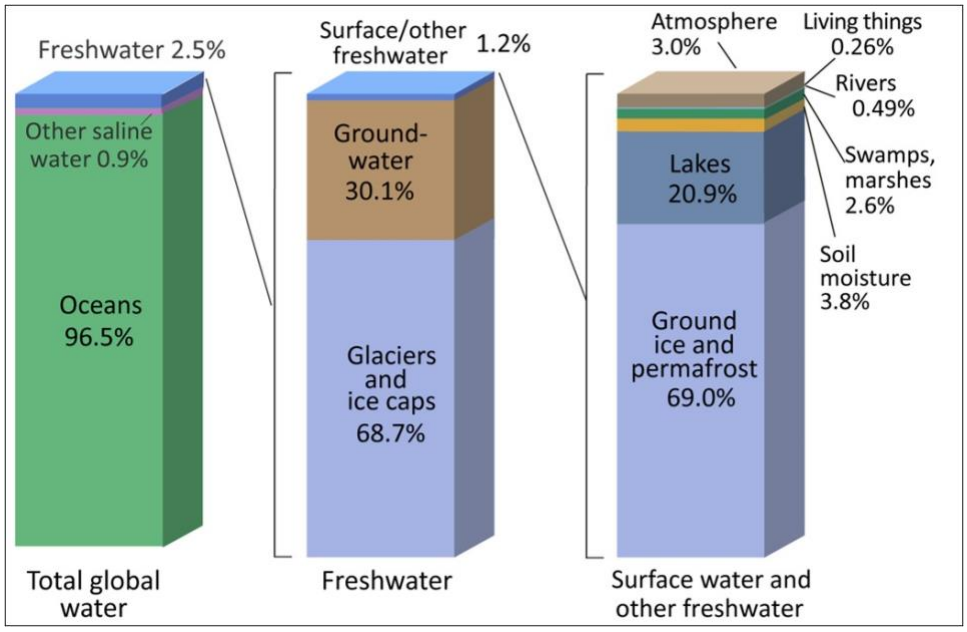


Figure 9.2: Most of the Earth's water is found in oceans and is therefore saltwater. Earth's freshwater sources are mostly locked within glaciers and ice caps and as groundwater. Rivers and lakes make up only a small fraction of Earth's freshwater resources.

Those who study water, water resources, or the landforms made by water, may have many titles, including hydrologist, hydro-geologist, geomorphologist, or geochemist, to name a few. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including in mining and natural resource extraction or in hazard mitigation and assessment. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible. Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara

Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 9.1: “The Water Cycle” (Public Domain; Howard Perlman and John Evans, USGS)
- Figure 9.2: “Where is Earth’s Water?” (Public Domain; USGS Water Science School)

Stream Drainage Basins and Patterns

The **drainage basin** of a stream includes all the land that is drained by one stream and all of its tributaries. Find out more about the drainage basin or watershed you live in by visiting the Environmental Protection Agency's How's My Waterway?.

The higher areas that separate drainage basins are called **drainage divides**. For North America, the **Continental Divide** in the Rocky Mountains separates water that drains west to the Pacific Ocean from water that drains east to the Gulf of Mexico or Atlantic Ocean (**Figure 9.3**).

Figure 9.3: Water that falls to the west of the continental divide will ultimately flow into the Pacific Ocean, whereas water that falls to the east will flow into the Atlantic Ocean or Gulf of Mexico.

As water flows over rock, it is influenced by it. Water follows the path of least resistance; this means it will weather and erode softer rock first, rather than more resistant rock. This can result in characteristic **patterns of drainage** (**Figure 9.4**). Some of the more common drainage patterns include:

- **Dendritic**: this drainage pattern indicates uniformly resistant bedrock that often includes horizontally layered sedimentary rocks. Since all the rock is uniform, the water is not

attracted to any one area, and spreads out in a branching pattern, like the branches of a tree.

- **Trellis:** this drainage pattern indicates alternating resistant and non- resistant bedrock that has been deformed (folded) into parallel ridges and valleys. The water erodes valleys in the softer rock, and appears much like a rose climbing on a trellis in a garden.
- **Radial:** this drainage pattern forms as streams flow away from a central high point, such as a volcano, resembling the spokes in a wheel.
- **Rectangular:** this drainage pattern forms in areas in which rock has been fractured by jointing or faulting which created weakened zones in the . Streams erode the weakened, less resistant rock and create a network of channels that make right-angle bends as they follow the intersecting fracture pattern. This pattern will often look like rectangles or squares.
- **Deranged:** this drainage pattern does not follow the rules. It consists of a random pattern of stream channels characterized by irregularity. It indicates that the drainage developed recently and has not had time to form one of the other drainage patterns yet.

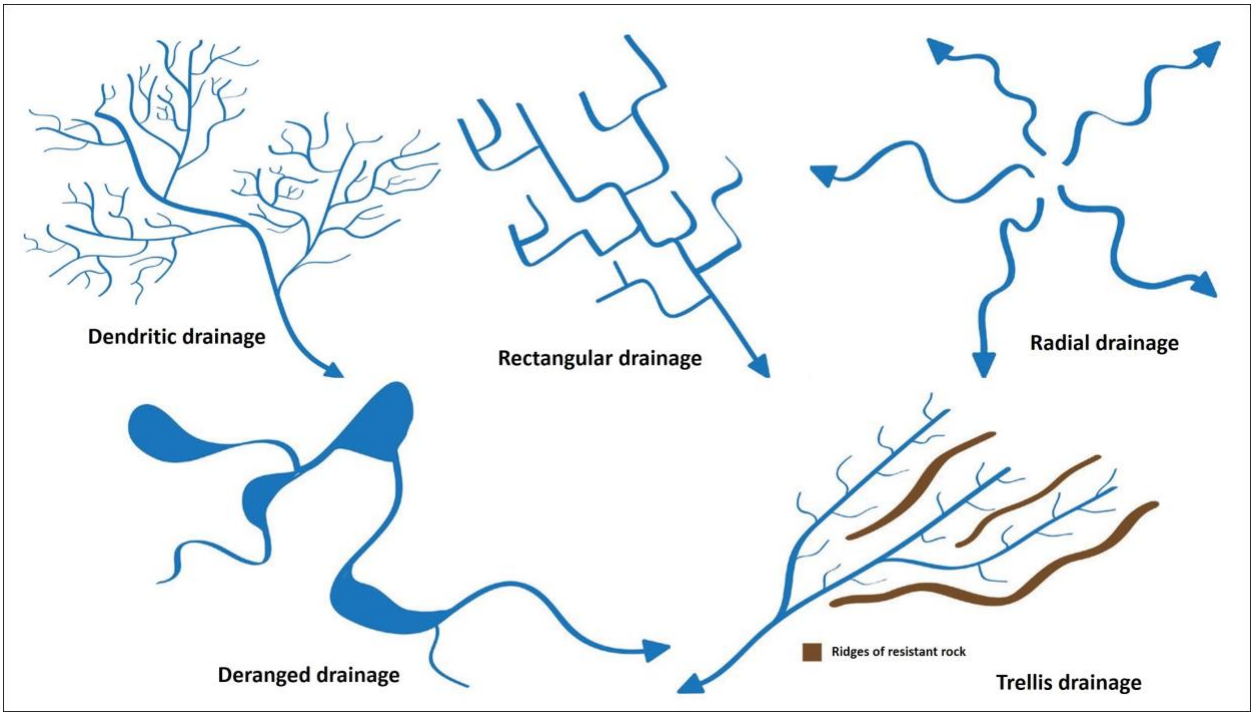


Figure 9.4: Drainage patterns.

Attributions

- Figure 9.3: “Continental Divide” (CC-BY 4.0; Chloe Branciforte via Google Earth)
- Figure 9.4: Derivative of “Drainage Patterns” (CC-BY-SA 3.0; Corey Parson via LibreTexts)

How Do Streams Move Sediment?

The running water in a stream will erode and move material within the **stream channel**. The transported material includes 1) the **dissolved load**, dissolved substances taken into solution during chemical weathering, 2) the **suspended load**, tiny silt and clay particles that are kept in suspension by the water's flow, and 3) the **bed load**, visible sand and gravel-sized sediments that typically travel along the stream bed. Here, grains move either via hopping (saltation), rolling, or sliding (traction) (**Figure 9.5**). The measure of the total sediment a stream can carry is called **stream capacity**.

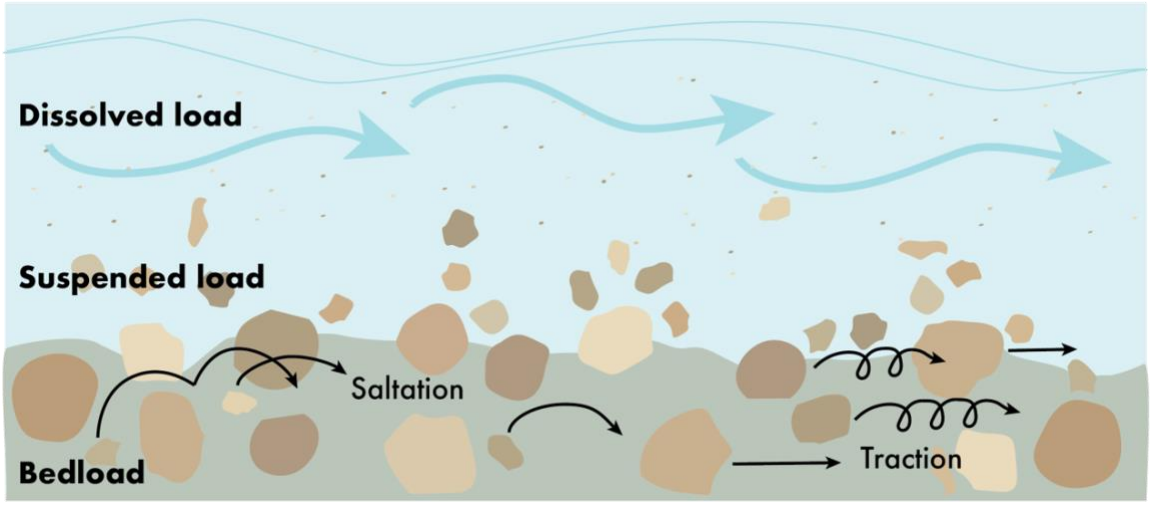


Figure 9.5: Streams carry sediment, including bigger pieces that are dragged, rolled or bounced along the base, smaller pieces that stay suspended within the water column, and ions that are dissolved within the water.

Stream competence reflects the ability of a stream to transport a particular size of particle (e.g., boulder, pebble, etc.). An increased velocity of water flow increases stream competence, whereas a decreased velocity of flow decreases stream competence (**Figure 9.6**).

While the dissolved, suspended, and bed loads may travel long distances, they will eventually settle out and be deposited. These stream deposited sediments, called **alluvium**, are typically deposited during flood events. This is because to more effectively transport sediment, a stream needs energy. This energy is mostly a function of the amount of water and its velocity. A fast-moving stream is more capable of carrying much more and larger sediment. As a stream loses energy, it will slow down, which is why deposition occurs.

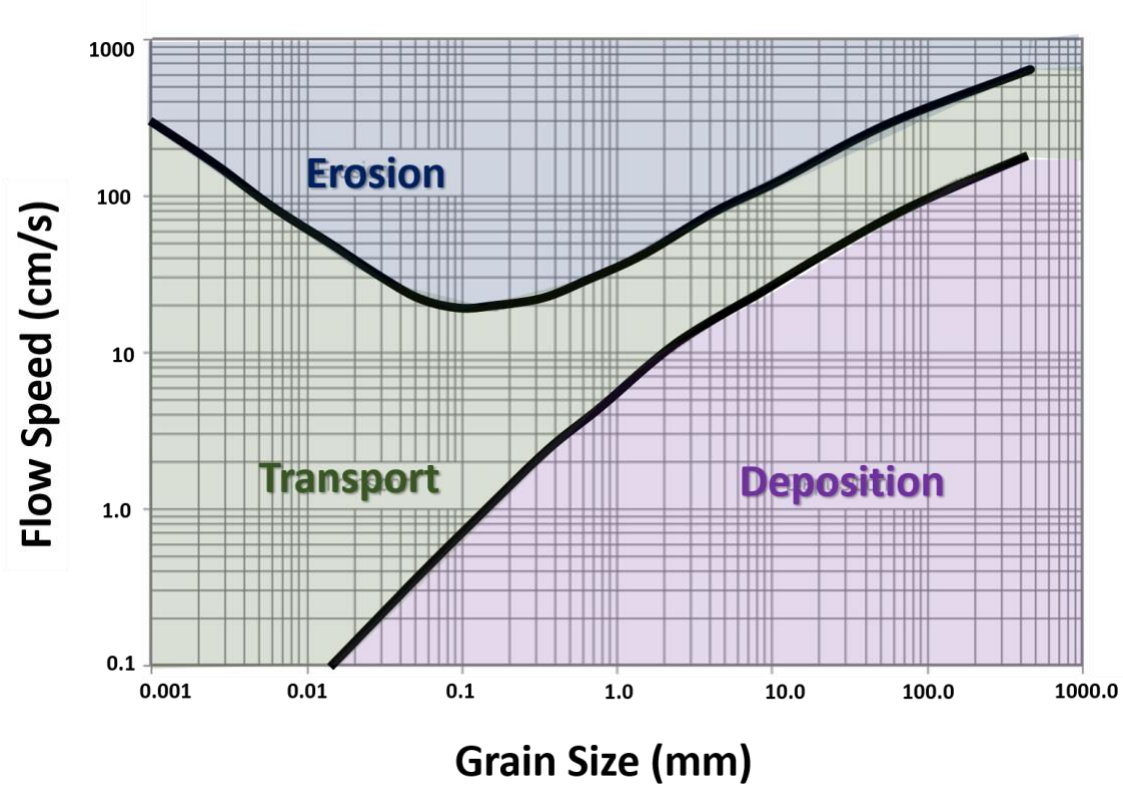


Figure 9.6: Hjulström Curve chart, describing the transport, deposition and erosion in flowing water.

Under normal conditions, water will remain in a stream channel. When the amount of water in a stream exceeds its banks, the water that spills out of the channel will rapidly decrease in velocity. A decrease in velocity results in the deposition of the larger sandy material the river carries along the channel margins. These ridges of sandy alluvium are natural levees (**Figure 9.7**). As numerous flooding events occur, these ridges build up under repeated deposition. These levees are part of a larger landform known as a **floodplain**. A floodplain is the relatively flat land adjacent to the stream that is subject to flooding during times of high discharge.

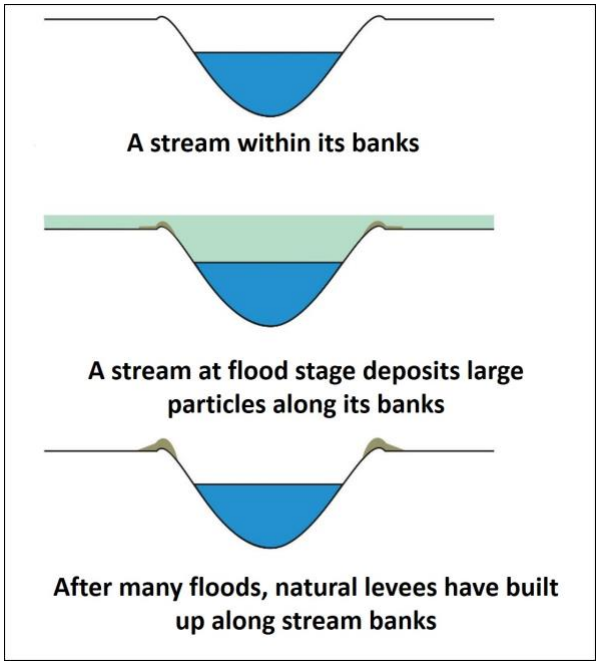


Figure 9.7: After many floods, natural levees have built up along stream banks.

Attributions

- Figure 9.5: “Stream Load” (CC-BY 4.0; Emily Haddad)
- Figure 9.6: Derivative of “Hjulströms diagram en” (CC-BY-SA 3.0; Karrock via Wikimedia Commons) by Chloe Branciforte
- Figure 9.7: Derivative of “Levees” (CC-BY-SA 3.0; Julie Sandeen via LibreTexts) by Chloe Branciforte

How Do Streams Erode?

Rivers can erode laterally (sideways), vertically (downcutting) or back into the upland area (headward erosion), all of which result in the river becoming wider, deeper, and longer (**Figure 9.8**). **Headward erosion** occurs when the river erodes in an upstream direction, lengthening the river valley. **Downcutting**, or vertical erosion, occurs as the river erodes downwards, deepening the river channel. **Lateral erosion** occurs along the edges (banks) of the river, widening the river valley.

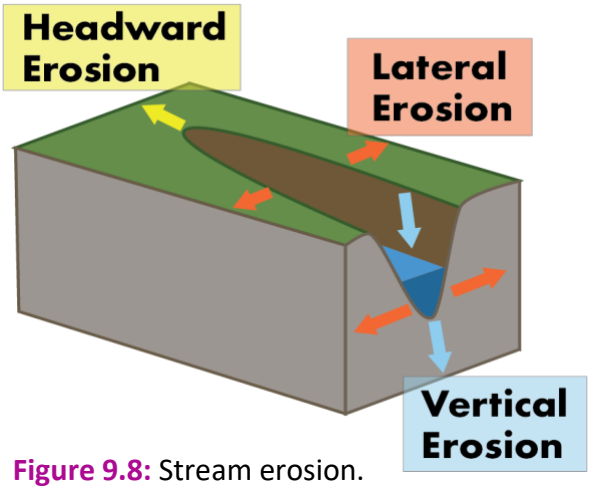


Figure 9.8: Stream erosion.

Stream gradient refers to the slope (rise over run) of the stream's channel. It is the vertical drop of the stream over a horizontal distance. Gradient can be calculated by using the following equation: **Gradient = (change in elevation) / distance.** Stream gradients tend to be higher at a stream's source, or the **headwaters**, and lower at the **mouth**.

Examine **Figure 9.9**. We want to determine the gradient from A to B. The elevation of the stream at A is 980', and the elevation of the stream at B is 920'. Referencing the scale bar, the distance from A to B is about 2 miles. Using the equation above: Gradient = (980'-920') / 2 miles, or 30 feet/mile (read 30 feet per mile).

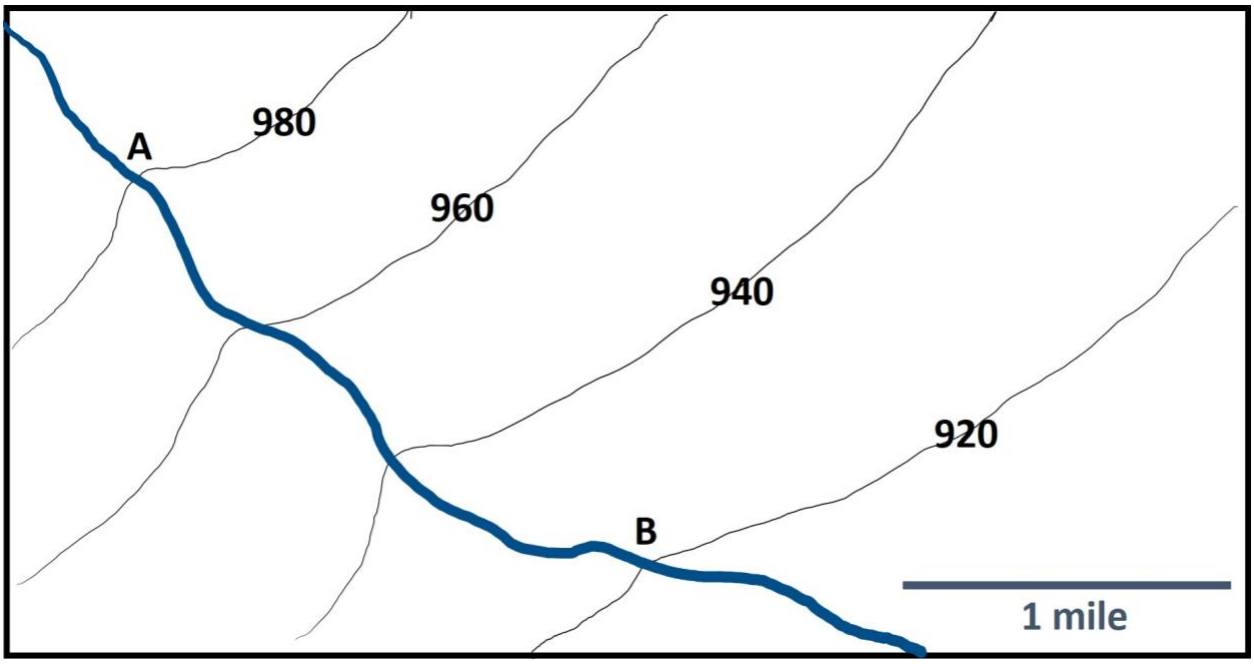


Figure 9.9: Calculating gradient.

Attributions

- Figure 9.8: “Stream Erosion” (CC-BY 4.0; Emily Haddad, own work)
- Figure 9.9: Derivative of “Gradient Calculation” (CC-BY-SA 3.0; Randa Harris via LibreTexts) by Chloe Branciforte

How Is Streamflow Measured?

The United States Geological Survey (USGS) is one of the major organizations tasked with measuring streamflow here in the US. More information about how they do that is available via their Streamflow Measurement website.

In general, **discharge** measures stream flow at a given time and location. It is a measurement of the volume of water passing a particular point during a period of time. Discharge can be calculated by using the following equation, **Discharge = Area * Velocity.** Area is determined by multiplying the width by the depth of the stream channel. Velocity of the water is typically measured in units of feet per second or meters per second, while discharge has units of cubic feet per second (cfs) or cubic meters per second (cfm). Discharge increases downstream in most rivers, as tributaries join the main channel and add water.

Sediment load also changes from headwaters to mouth. At the headwaters, tributaries quickly carry the load downstream, combining with loads from other tributaries. The sediment is eventually deposited when the stream reaches **base level**. Occasionally during this process of transporting material downstream, the sediment load is large enough that the water is not capable of transporting it, so deposition occurs. If a stream becomes overloaded with sediment, a **braided stream** may develop. Typically, these streams have a network of intersecting channels that resembles braided hair with sand and gravel bars common. Braided streams are common in sediment-abundant areas, near glaciers or in arid and semiarid regions with high erosion rates.

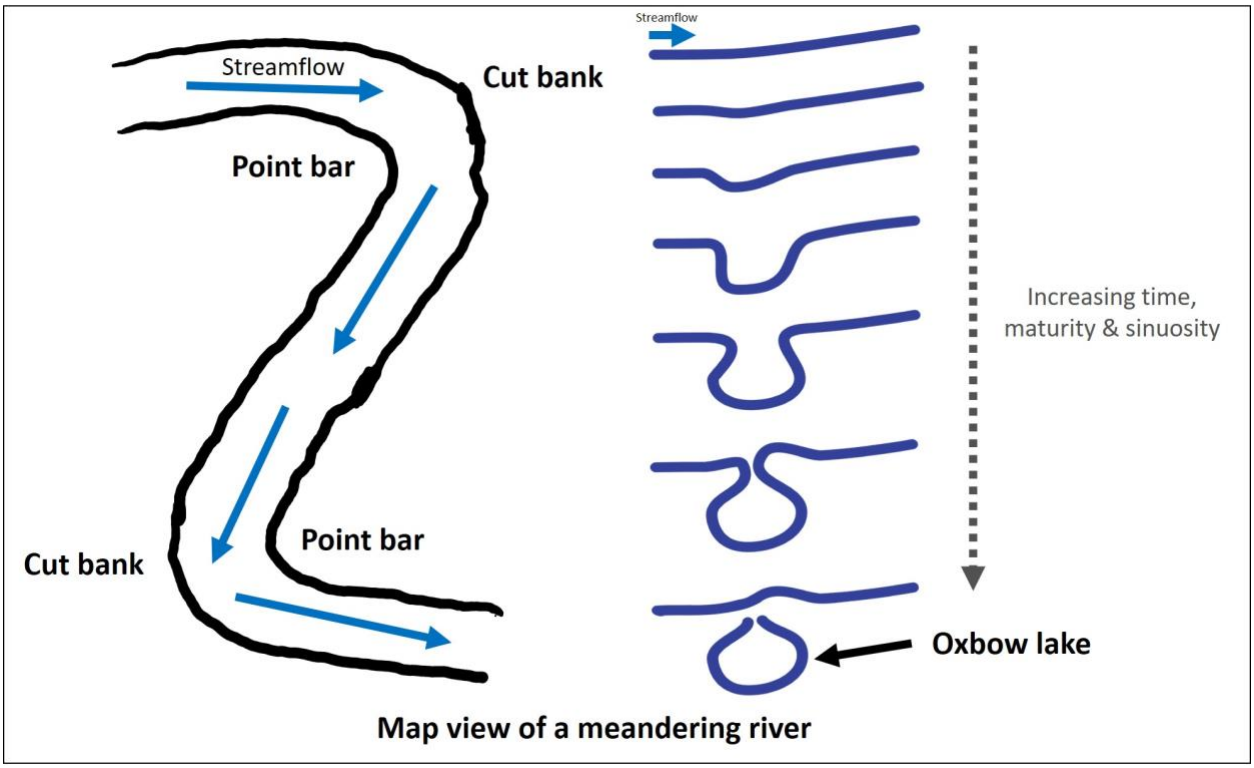


Figure 9.10: *Left:* Parts of a meandering stream. The S-curves are meanders. The arrows within the stream depict where the fastest water flows. That water erodes the outside bank, creating a steep bank called the cut bank. The slowest water flows on the inside of the meander, slow enough to deposit sediment and create the point bar. *Right:* Formation of an oxbow lake. A meander begins to form and is cut off, forming the oxbow.

Streams may also be **meandering**, with broadly bending meanders that resemble "S"-shaped curves. Water will travel the fastest on the outside of a bend. This higher velocity leads to more erosion on the outside bend, forming a **cut bank**. Erosion at the cut bank is offset by deposition on the opposite bank of the stream, where the water moves slower and allows sediment to settle out and deposit. These areas of deposition are called **point bars.** As meander bends become more complicated, or sinuous, they may intersect to form a cutoff, which shortens the stream's path. After cutoff the abandoned meander loop becomes a crescent-shaped **oxbow lake** (**Figure 9.10** and **9.11**).

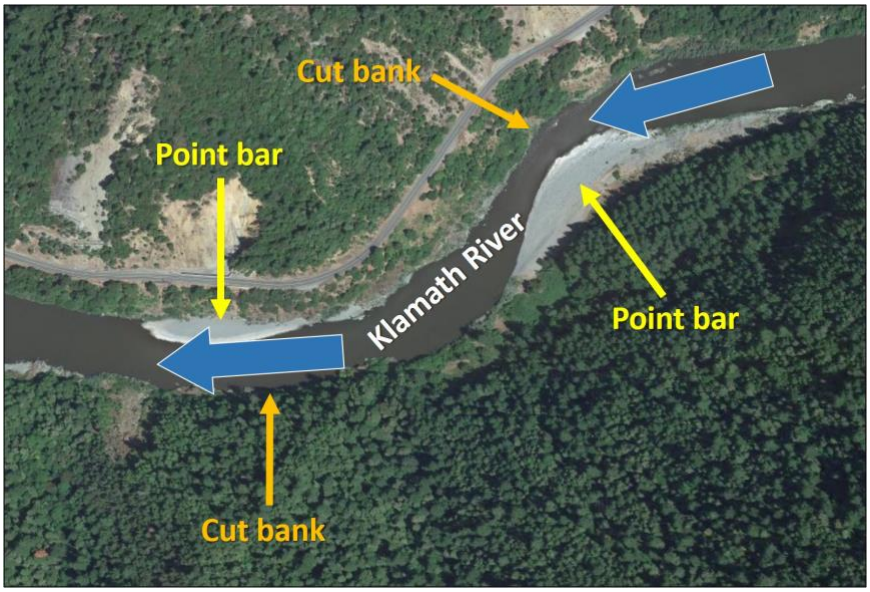


Figure 9.11: Klamath River, illustrating the cut bank and point bar areas.

Straight streams, in which channels remain nearly straight, are uncommon. They can form naturally due to a linear zone of weakness in the underlying rock or can be human constructed, in an effort at flood control, much like what has been done with the Los Angeles River (**Figure 9.12**).

Figure 9.12: Aerial photo of the Los Angeles River.

Attributions

- Figure 9.10: Derivative of “Meandering River” (CC-BY-SA 2.5; Maksim via Wikimedia Commons) by Chloe Branciforte
- Figure 9.11: “Klamath River” (CC-BY 4.0; Chloe Branciforte via Google Earth)
- Figure 9.12: “LA River” (CC-BY-SA 3.0; Joe Mabel via Wikimedia Commons)

Flood Stage and Flooding

Flooding is a common and a serious problem on and along our nation's waterways. **Flood stage** is reached when the water level in a stream overflows its banks. **Floodplains** are popular sites for development but are best left for playgrounds, golf courses, and the like.

Have you ever heard someone say, "that flood was a 1 in 100-year flood"? What does this mean? Does it mean that a flood will only occur every 100 years, and that we are safe the other 99? The short answer is No; on average, we can expect a flood of this size or greater to occur within any 100-year period. However, we cannot predict whether it will occur in any particular year, only that each year has a 1 in 100 (1%) chance of occurring in any year. The timing between these major flooding events, or any major geologic event (drought, volcanic eruption, earthquake, tsunami, etc.), is referred to as a **recurrence interval**. This is the average time period within which a given flood event will be equaled or exceeded once.

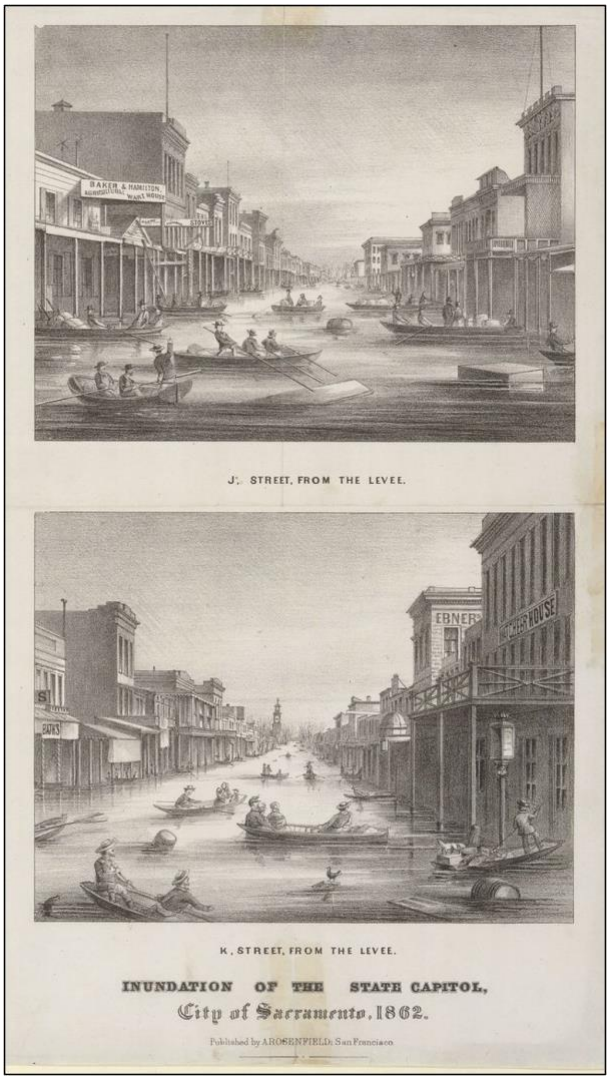


Figure 9.13: J and K streets in downtown Sacramento seen from levee illustrating the impact of the Great California Flood of 1862; people in boats make their way between buildings in flooded city streets.

In order to better understand stream behavior, the **USGS** has installed thousands of stream gauges throughout the country, locations with a permanent water level indicator and recorder. Data from these stations can be used to make flood frequency curves, which are useful in making flood control decisions.

Attributions

- Figure 9.13: “Inundation of the State Capitol, City of Sacramento, 1862” (Public Domain; A. Rosenfield via Calisphere)

Activity 9A: Recurrence Intervals and the Russian River

Recall that a **recurrence interval** (or return period) is based on the probability that a given event, in this case a flood of specific magnitude, will be equaled or exceeded in any given year. For example, a "1 in 100-year flood event" means on average, we can expect a flood of this size or greater to occur within any 100-year period. However, we cannot predict it will occur in any particular year, only that each year has a 1 in 100 (1%) chance of occurring in any year.

Data for this activity was collected from the USGS peak streamflow for the Russian River, located in northern California south of Ukiah. The chart below includes the 20 largest discharge events for Russian River at USGS station 11467000 from February 28, 1940 – February 27, 2019.

Step 1: To create a flood frequency graph, we must calculate the recurrence interval. First, however, we need to rank the flood events on the chart below. The bigger the stream flow (cfs, read as cubic feet per second), the higher the discharge. A 1 signifies the highest discharge event and a 20 the lowest discharge event (see table below).

Date	Stream flow (cfs)	Flood Rank	Recurrence Interval (years)	Probability (%)
Feb. 28, 1940	88,400			
Feb. 06, 1942	67,800			
Jan. 22, 1943	69,200			
Dec. 23, 1955	90,100			
Feb. 25, 1958	68,700			
Feb. 01, 1963	71,800	1	80	1.25
Dec. 23, 1964	93,400			
Jan. 05, 1966	77,000			
Jan. 21, 1967	68,400			
Jan. 14, 1969	68,600			
Jan. 24, 1970	72,900			
Jan. 17, 1974	74,000			
Feb. 13, 1975	67,300			
Dec. 20, 1981	67,200			
Jan. 27, 1983	71,900			
Feb. 18, 1986	102,000			
Jan. 09, 1995	93,900			
Jan. 01, 1997	82,100			
Jan. 01, 2006	86,000			
Feb. 27, 2019	72,000			

Table 9.1: 20 largest discharge events for Russian River at USGS station 11467000 from February 28, 1940 – February 27, 2019.

Step 2: Calculate the recurrence interval for each discharge event using the following equation:

$$RI = \frac{n+1}{m}$$

Where,

RI = Recurrence Interval (in years)

n = number of years of record (in this case, 79)

m = rank of flood (see table)

Example: Feb. 18, 1986

RI = (79 + 1) / 1

RI = 80 (Note: It is ok to round to the nearest tenth)

Step 3: Calculate the probability of each discharge event:

$$Probability = \left(\frac{1}{RI}\right) * 100$$

Where,

RI = Recurrence Interval (from Step 2)

Example: Feb. 18, 1986

*Probability = (1/80) * 100*

*Probability = 1.2% (**Note: round to the nearest tenth)***

What does this calculation signify? *On average a flood event of this magnitude, discharge of 102,000 cfs (cubic feet per second), occurs every 80 years. This does not preclude the event from happening every year, but the probability of that is small (~1.25%).*

Step 4: Now that the table has been completed, plot the discharge against the recurrence interval on the graph below. After plotting each point, use a ruler or other straightedge to draw a **best fit line**.

What is a best fit line? *It is a straight line on a graph that shows the general direction that a group of points appear to be heading, however it does not connect all points on the graph.*

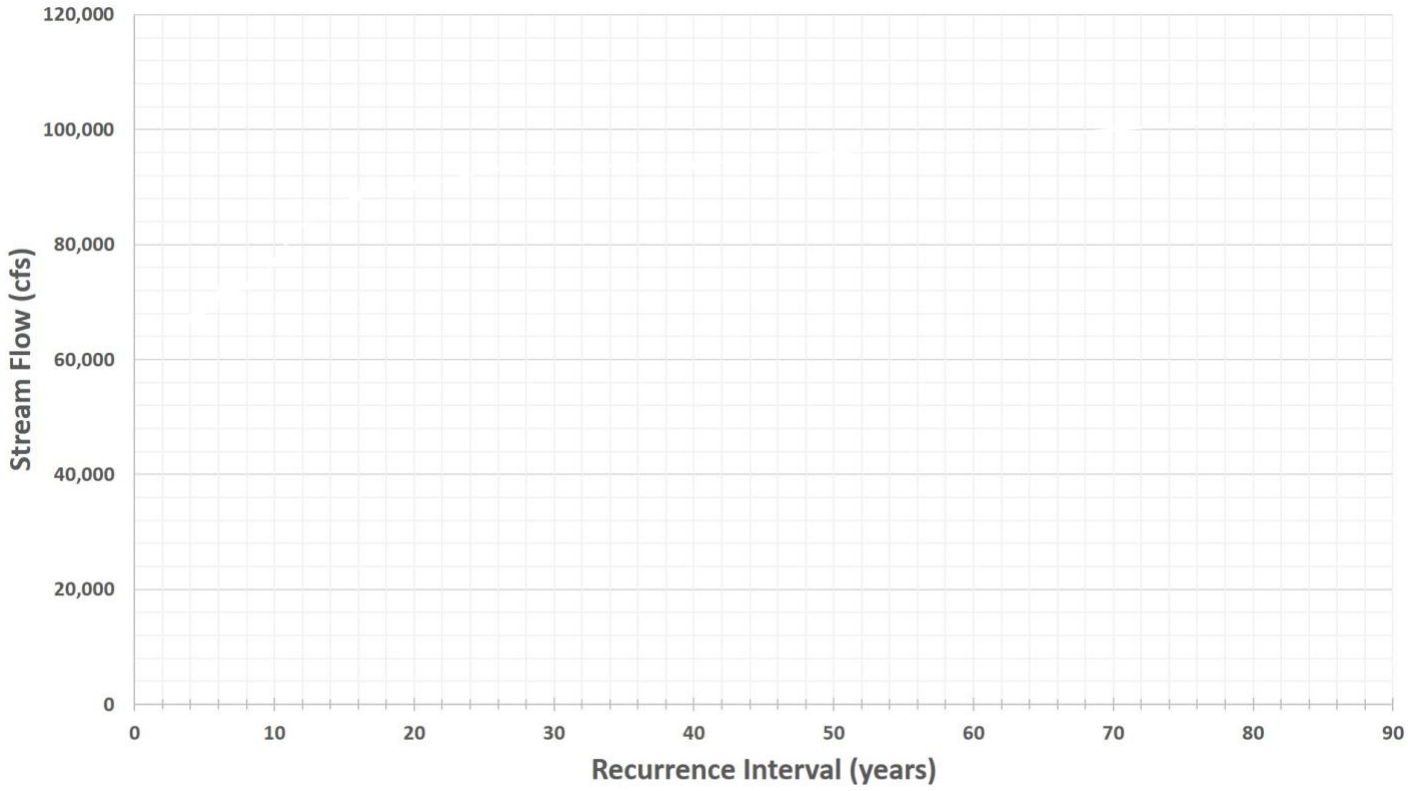


Figure 9.14: Graph to use for Activity 9A: Recurrence Intervals and the Russian River.

Step 5: Answer the following questions based on **Table 9.1** and **Figure 9.14** from above.

1. On which date did a flood event have a recurrence interval of 10?
    a. 1/5/1966
    b. 1/17/1974
    c. 12/20/1981
    d. 2/18/1986

2. Of the following dated flood events, which one would you expect to happen more often?
    a. 12/23/1955
    b. 2/1/1958
    c. 2/18/1986
    d. 1/1/2006

3. Observe your best fit line. What *approximate* discharge would be associated with a 50-year recurrence interval?
    a. 82,000 cfs
    b. 88,000 cfs
    c. 94,750 cfs
    d. 98,000 cfs

4. Is it possible that a flood with a similar discharge to that of the event from 2/27/2019 could happen again in the next 10 years?

    a. Yes or no?

    b. Why or why not?

Attributions

- Table 9.1: “Peak Streamflow for the Russian River” (Public Domain; Chloe Branciforte and Emily Haddad via USGS/NWIS)
- Figure 9.14: “Recurrence Interval Graph” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 9B: Surface Water on Mars

Mars has shown evidence of water, and NASA and others have been studying Mars intensely in recent years. Let us look at a few features on Mars.

Use Google Mars, ***or*** download the desktop version of Google Earth.

If using the desktop version, locate Saturn in the toolbar along the top. Click the Saturn button to bring up several location options and select Mars. In the Layers box on the left, notice Global Maps. You may have to click on it to expand it. For today, we will use the highest quality images found in the Visible Images layer. The other layers are interesting but won't be used here.

1. In the Search tab of either platform, type in Noctis Labyrinthus and zoom out enough to see the entire landscape (see **Figure 9.15**). Notice the linear valleys. Assume that water flowed through these valleys at some time. What type of drainage pattern would this area represent?

a. Trellis
b. Dendritic
c. Rectangular
d. Radial
e. Deranged

2. Think about the drainage pattern you selected in the previous answer. What does this tell you about the underlying rocks?

a. the rocks are probably fractured
b. the rocks are uniformly resistant
c. the rocks are part of a topographic high, like a mountain
d. the rocks are alternately resistant and non-resistant

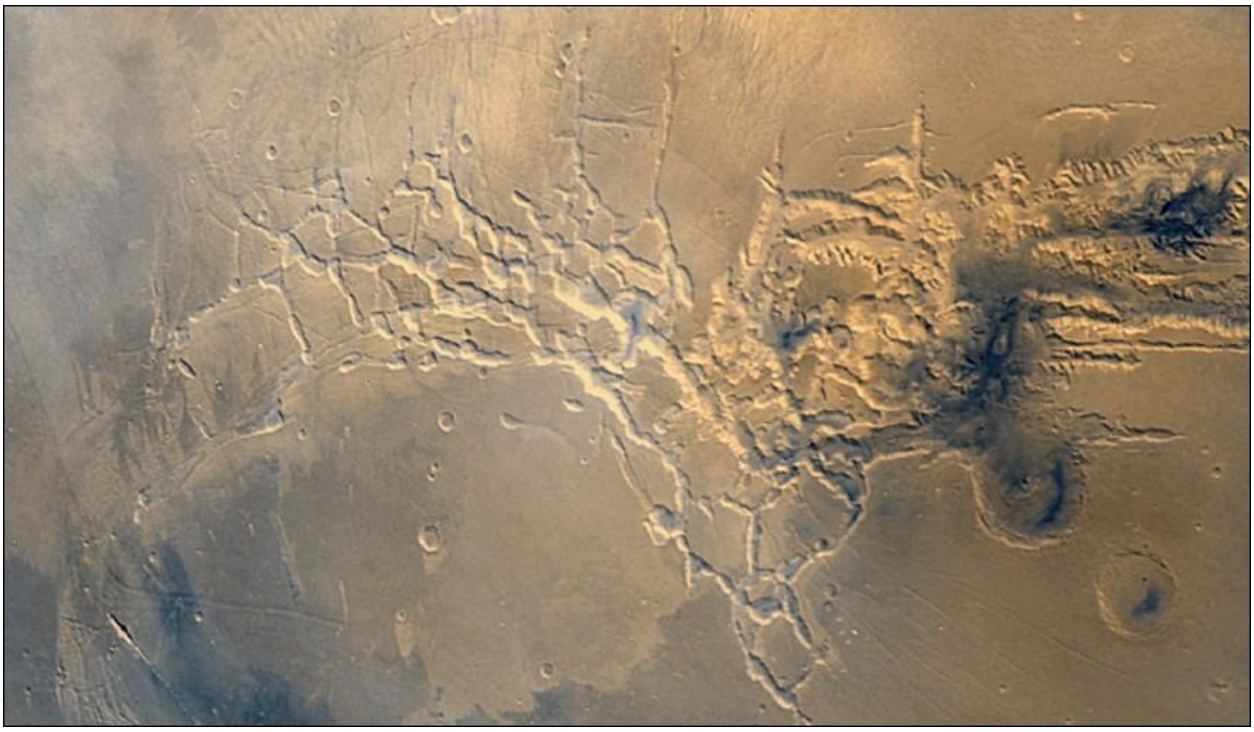


Figure 9.15: Martian drainage system to identify in Activity 9B.

3. In the Search tab of either platform, type in Warrego Valles and zoom to ~120 miles. In Google Mars, you will have to select the Infrared tab for the best visualization (see **Figure 9.16**). Current research suggests this drainage pattern formed by the runoff of either precipitation or groundwater. What type of drainage does this appear to be?

a. Trellis
b. Dendritic
c. Rectangular
d. Radial
e. Deranged

Figure 9.16: Aerial view of a Martian drainage system at Warrego Valles for Activity 9B.

Consider the following image (**Figure 9.17**), a side-by-side of both the Martian and Earth surface. The Martian Rover, Curiosity, is responsible for imaging the surface of Mars below.

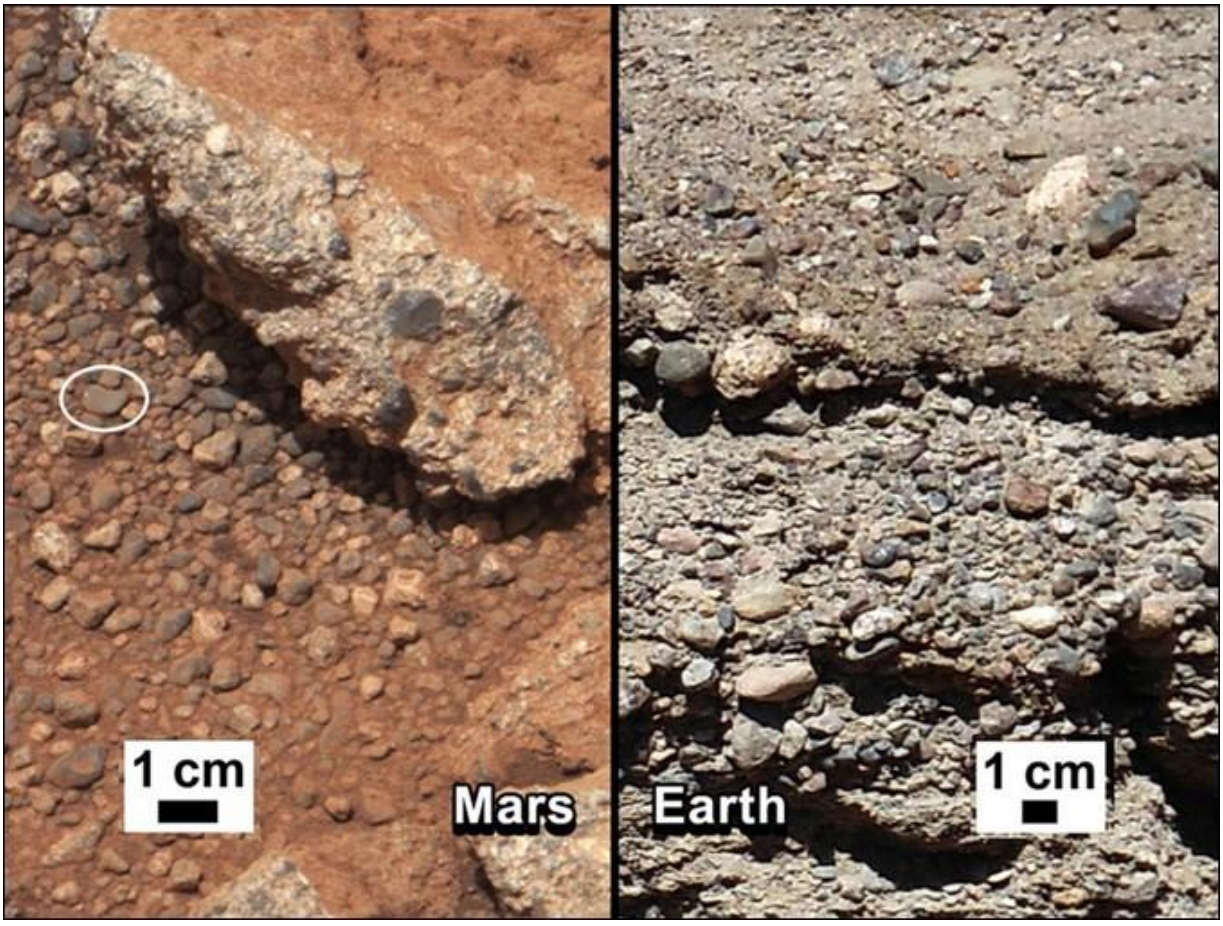


Figure 9.17: The outcrop of rocks on Mars (left) with similar rocks seen on Earth (right) to be used for identification in Activity 9B.

5. We have not yet sent a crewed mission to Mars; however, Martian Rovers, like Curiosity, help image and collect information for geologists. Despite never setting foot on Mars, geologists are still able to make observations and complete research. To do this we must utilize all that is available to us, including Lyell's **Geologic Principles**. Which Principle(s) could a planetary geologist apply to this image?

6. What type of rock is present in both images?

- **a.** Igneous
- **b.** Metamorphic
- **c.** Sedimentary

7. What could this information signify to planetary geologists about the past surface conditions on Mars?

Attributions

- Figure 9.15: “Martian Drainage” (Public Domain; NASA)
- Figure 9.16: “Warrego Valles” (CC-BY 4.0; Chloe Branciforte via Google Mars)
- Figure 9.17: “Rock Outcrops on Mars and Earth” (Public Domain; NASA)

Activity 9C: Surface Water on Earth

The exercises that follow use the browser version of Google Earth. For each question (or set of questions) paste the location that is given into the "Search" box. Examine each location at multiple eye altitudes and differing amounts of tilt. For any measurements access the ruler via the icon in the toolbar.

1. Search for 39°35'42.5"N 121°59'23.3"W, and zoom out to an eye altitude (Camera) of 24,500 feet. How would one describe the adjacent river?
    - **a.** Straight
    - **b.** Meandering
    - **c.** Low sinuosity
    - **d.** Braided

2. In this type of stream, where does erosion occur?
    - **a.** Why?

3. In this type of stream, where does deposition occur?
    - **a.** Why?

4. Search for 36°12'30.3"N 116°54'18.0"W and zoom out to an eye altitude (camera) of ~30,000 feet. How would one describe these rivers?
    - **a.** Straight
    - **b.** Meandering
    - **c.** Low sinuosity
    - **d.** Braided

5. What factors control the course of this river?
    - **a.** Steep gradient and high discharge
    - **b.** Low gradient and low discharge
    - **c.** Low gradient and abundant sediment supply
    - **d.** Steep gradient and low sediment supply

6. Search for 38°01'12.2"N 121°43'20.0"W and zoom out to an eye altitude of 30,000 feet. The river in this area has a rather interesting pattern, what appeared to happen here?
    - **a.** a meander eroded through its bank and created an oxbow lake
    - **b.** the river is in a karst terrain and disappeared into the ground
    - **c.** the river is following patterns, likely faults, in the underlying bedrock
    - **d.** during a flood, the river breached the natural levee flowing into the floodplain

7. Search for 41 24 30.77N 122 11 46.23W and zoom to an eye altitude of 20 miles. What type of drainage pattern is present in this area?

- **a.** Trellis
- **b.** Dendritic
- **c.** Rectangular
- **d.** Radial
- **e.** Deranged

8. What does this type of drainage pattern indicate about the area?

- **a.** rocks in the area are homogeneous and/or flat lying
- **b.** rocks in the area are alternating resistant and non-resistant, forming parallel ridges and valleys
- **c.** stream channels radiate outward like wheel spokes from a high point
- **d.** stream channels flow randomly with no relation to underlying rocks or structure

Activity 9D: The Great Flood of California (1862)

In the winter of 1861-62, rain across the West created the worst flooding in the history of California, Oregon, and Nevada, killing thousands, more than 1% of the population at the time, and bankrupting the state. A 300-mile stretch of California's Central Valley, the center of its agriculture, was covered thirty feet deep in water. Yet most Californian's have never heard of it. (*The Big Ones*, L. Jones, 2018).

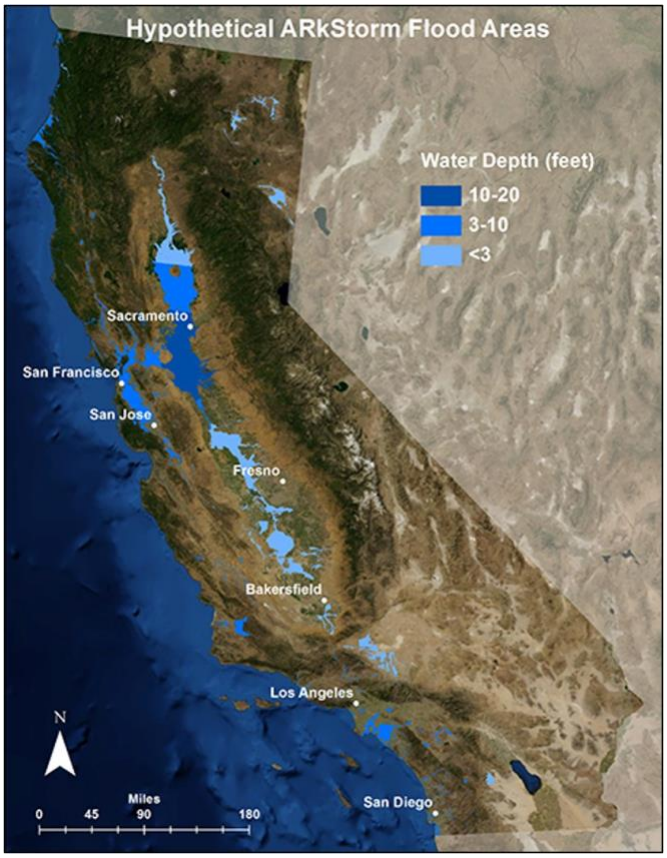


Figure 9.18: A diagram of the flood areas of the December 1861-January 1862 California Megastorm. These same areas are expected to flood again if another megastorm were to impact California.

Unfortunately, due to climate change, storms of this magnitude will become more frequent and intense. To prepare communities the USGS developed a simulation, ARkStorm, to address these massive storms (**Figure 9.18**). Experts from scientific research agencies were assembled and tasked with designing a large, but scientifically plausible, hypothetical storm scenario that hit both northern and southern California. The wind, precipitation, flooding, and coastal hazards were translated into physical, environmental, social, and economic damages to provide emergency responders, resource managers, and the public a realistic assessment of what is historically possible.

1. Watch this USGS video on the Great Flood and ARkStorm simulation.

2. Should the Great Flood occur again, today, what ramifications and impacts would affect our communities and state?
    a. What areas would be affected most? Why?

    b. What industries would be affected?

c. Would this affect anyone beyond California, why or why not?

3. The video asks an important question: how will society deal with the social, economic and environmental impacts from a flood of this magnitude? The ARkStorm simulation was developed to give scientists and communities the opportunity to begin planning and preparing for this future event. After all, natural hazards are only hazards because of humans. Hazard science tries to understand the hazard and develop action plans to reduce the impact on us. ***In your opinion, what can we do proactively to reduce our future hazard potential when it comes to a flood of this magnitude?***

4. Want to know more about the Great Flood and ARkStorm? Consider reading these,
   a. Mother Jones: The Biblical Flood That Will Drown California (2020)
   b. Scientific American: The Coming Megafloods (2013)

Attributions

- Figure 9.18: “ARkStorm” (Public Domain; USGS via Wikimedia Commons)

Chapter 10: Landslides and Mass Wasting

Learning Outcomes

After completing this chapter, you should be able to:

- ✓ Identify and describe types of mass wasting.
- ✓ Describe some of the measures that can be taken to mitigate the risks associated with mass wasting.

Thumbnail for Chapter 10:

Thumbnail: "Big Sur Landslide on May 20, 2017" (Public Domain; USGS)

What Is Mass Wasting?

Mass wasting is the downhill movement of rock and soil material due to gravity. The term **landslide** is often used as a synonym, but mass wasting is a much broader term referring to all movement downslope. Movement by mass wasting can be slow or rapid. Rapid movement can be dangerous, such as during debris flows. Recall that **erosion** is a powerful and continuous process and therefore landslides can be devastating and costly. In California, we have many regions with a high potential for landslides, particularly if you live near the coast, mountains, or a recent burn area (**Figure 10.1**).

Figure 10.1: The Mud Creek landslide near Big Sur, California.

Those who study mass wasting are typically referred to as geomorphologists or hazard scientists. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including hazard mitigation and assessment. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and

science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 10.1: “Big Sur Landslide on May 20, 2017” (Public Domain; USGS)

Mass Wasting Categories

Mass wasting can be subdivided by type of movement (falls, flows and slides), the overall geologic material (bedrock, debris, or earth) (**Table 10.1**), and the average rate of movement (**Table 10.2**). Mass wasting types often share common morphological features observed on the surface: **head scarps** commonly seen as crescent shapes on a cliff face; hummocky or uneven surfaces; accumulations of **talus** (loose rocky material falling from above); and toe of slope, which covers existing surface material.

Category of Movement	Subcategory of Movement	Material	Speed
Falls	*Rock Fall*	Rock	Extremely rapid
	Rock/Block Avalanche	Rock	Very rapid
	Topple	Rock, soil, debris	Extremely rapid
Flows	*Debris flow*	Rock, soil, debris, water	Extremely rapid to rapid
	Mud flow	Soil (mud & silt), water	Extremely rapid to rapid
	Earth flow	Soil and debris	Moderate to slow
	Creep	Soil	Extremely slow
Slides	*Translational slide*	Rock, soli, debris	Extremely rapid to very slow
	Rotational slide	Soil and debris	Extremely slow to moderate

Table 10.1: Major categories and subcategories of mass wasting.

Approximate Rates of Movement for Mass Wasting	
Extremely rapid to very rapid	3 m (10 ft) per second
Rapid	0.3 (1 ft) per minute
Moderate	1.5 m (5 ft) per day
Slow	1.5 (5 ft) per month
Very slow:	1.5 (5 ft) per year
Extremely slow	0.3 m (1 ft) per 5 years

Table 10.2: Qualitative and quantitative comparison of the rates of movement for mass wasting categories.

Falls

Falls are abrupt movements of masses of geologic materials, such as rocks and boulders, that become detached from steep slopes or cliffs (**Figure 10.2**). Separation occurs along natural breaks, like fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and water. Yosemite National Park is well known for its impressive rock falls.

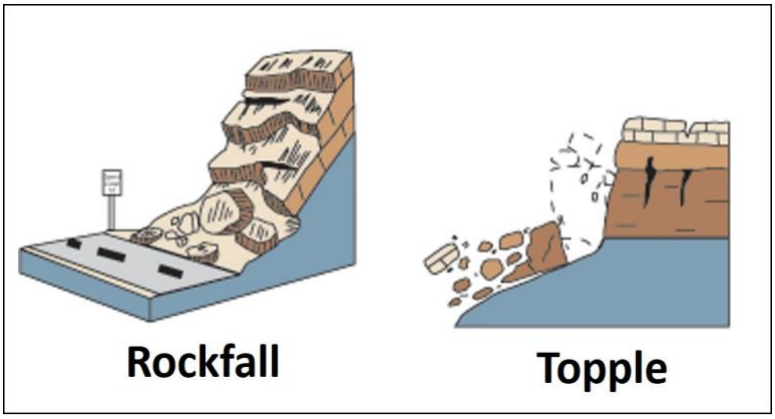


Figure 10.2: Rockfall and topple.

Mass Wasting: Falls			
Category of Movement	**Subcategory of Movement**	**Material**	**Speed**
Falls	*Rock Fall*	Rock	Extremely rapid
	Rock/Block avalanche	Rock	Very rapid
	Topple	Rock, soil, debris	Extremely rapid

Table 10.3: Rock falls, rock/block avalanches, and topples are all examples of falls.

Flows

Flows are rapidly moving mass wasting events in which the loose material is typically mixed with abundant water, creating long run outs at the slope base (**Figure 10.3**). Depending on the type of material involved and the amount of water, flows can be separated into **debris flow** (coarse material), **mudflow** (fine material, faster), and **earthflow** (fine material, slower). **Creep** is the imperceptibly slow downward movement of material caused by a regular cycle of nighttime freezing followed by daytime thawing in unconsolidated material such as soil. During the freeze, expansion of ice pushes soil particles out away from the slope, while the next day following the thaw, gravity pulls them directly downward. The net effect is a gradual movement of surface soil particles downhill. Creep is indicated by curved tree trunks, bent fences or

retaining walls, tilted poles or fences, and small soil ripples or ridges. A special type of soil creep is **solifluction**, which is the slow movement of soil lobes on low-angle slopes due to soil seasonally freezing and thawing in high-latitude, typically sub-Arctic, Arctic, and Antarctic locations.

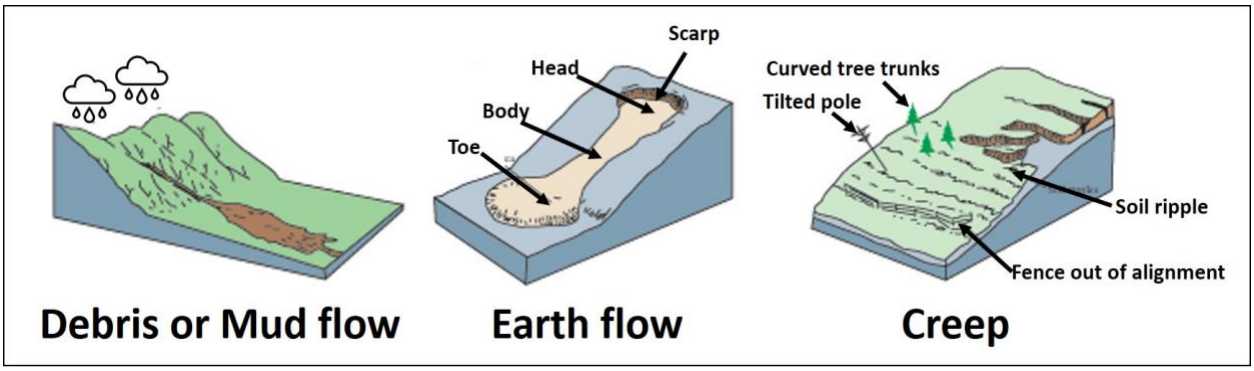


Figure 10.3: Flows and creep.

Mass Wasting: Flows			
Category of Movement	**Subcategory of Movement**	**Material**	**Speed**
Flows	*Debris flow*	Rock, soil, debris, water	Extremely rapid to rapid
	Mudflow	Soil (mud & silt), water	Extremely rapid to rapid
	Earthflow	Soil and debris	Moderate to slow
	Creep	Soil	Extremely slow

Table 10.4: Debris flows, mudflows, earthflows, and creep are all examples of flows.

Slides

A **translational slide** is rock, soil or debris that moves along a sloping surface, similar to sliding down a playground slide (**Figure 10.4, right**). In most cases, the movement occurs along a plane of weakness and may run parallel to a fracture, bedding, or metamorphic foliation plane. **Rotational slides (or slumps)** commonly show slow movement along a curved rupture surface (**Figure 10.4, left**).

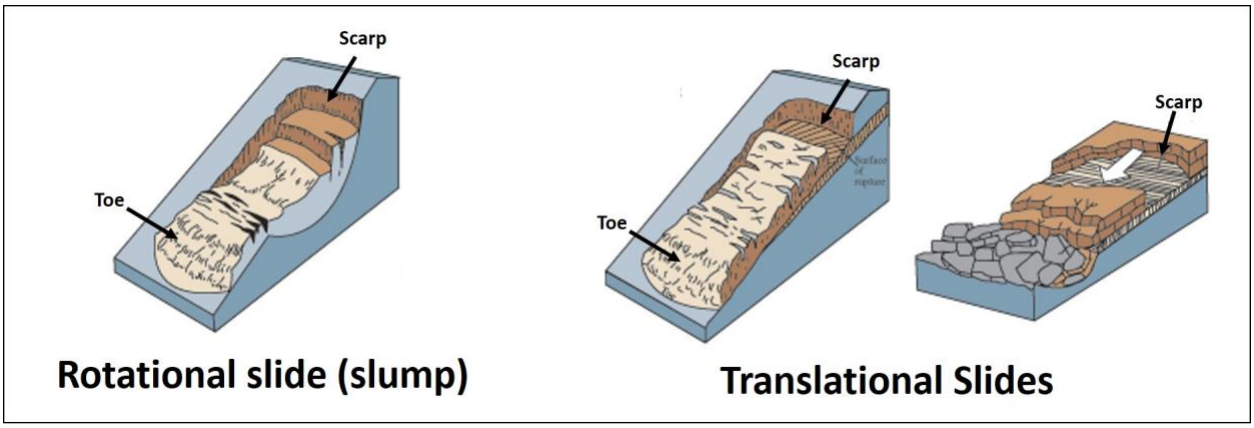


Figure 10.4: Slides and slumps.

Mass Wasting: Slides			
Category of Movement	**Subcategory of Movement**	**Material**	**Speed**
Slide	*Translational slide*	Rock, soil, debris	Extremely rapid to very slow
	Rotational (slump)	Soil and debris	Extremely slow to moderate

Table 10.5: Translational slides and rotational slides (slumps) are all examples of slides.

Attributions

- Table 10.1: “Mass Wasting Categories” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 10.2: “Approximate Rates of Movement for Mass Wasting” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 10.2: Derivative of “Landslide Types and Processes” (Public Domain; USGS) by Chloe Branciforte
- Table 10.3: “Mass Wasting: Falls” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 10.3: Derivative of “Landslide Types and Processes” (Public Domain; USGS) by Chloe Branciforte
- Table 10.4: “Mass Wasting: Flows” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 10.5: Derivative of “Landslide Types and Processes” (Public Domain; USGS) by Chloe Branciforte
- Table 10.5: “Mass Wasting: Slides” (CC-BY 4.0; Chloe Branciforte, own work)

Resisting vs. Driving Forces

Slope movement occurs when forces pulling down-slope (mainly gravity) exceed the strength and inertia of the earth materials that compose the slope. Mass wasting can be initiated on slopes already on the verge of movement by rainfall, snowmelt, changes in water level, stream erosion, changes in groundwater, earthquakes, volcanic activity, disturbance by human activities, or any combination of these factors.

The steepest angle at which rock and soil material is stable and will not move downslope is called the **angle of repose**, which is measured relative from the horizontal. When a slope is at its angle of repose, the shear force of gravity is in equilibrium with the normal force. If the slope becomes just slightly steeper, the shear force exceeds the normal force, and the material starts to move downhill. The angle of repose varies for all material and slopes depending on many factors, such as grain size, grain composition, and water content. In general, if the total shear force acting on the earth materials exceeds the total normal force acting on the earth materials, the slope will become unstable and a landslide is likely (**Figure 10.5**).

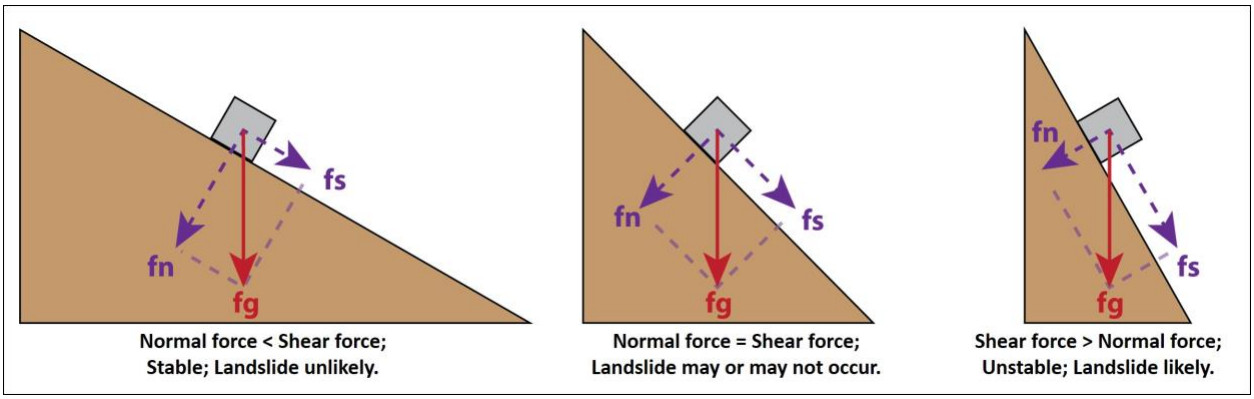


Figure 10.5: Differences in the shear and normal components of the gravitational force on slopes with differing steepness. The gravitational force is the same in all three cases.

There are several **contributing factors** that increase the effects of down-slope forces and weaken the cohesion of slope materials, thereby increasing the chance of a mass wasting. Some of these contributing factors can be prevented by human mitigation, while others we are unable to change.

Geology

The overall strength and composition of the rock, orientation of bedding, or foliation planes are all important contributing factors. For example, a bed oriented in the same direction as the slope is more likely to fail than bedding going against the slope (**Figure 10.6**).

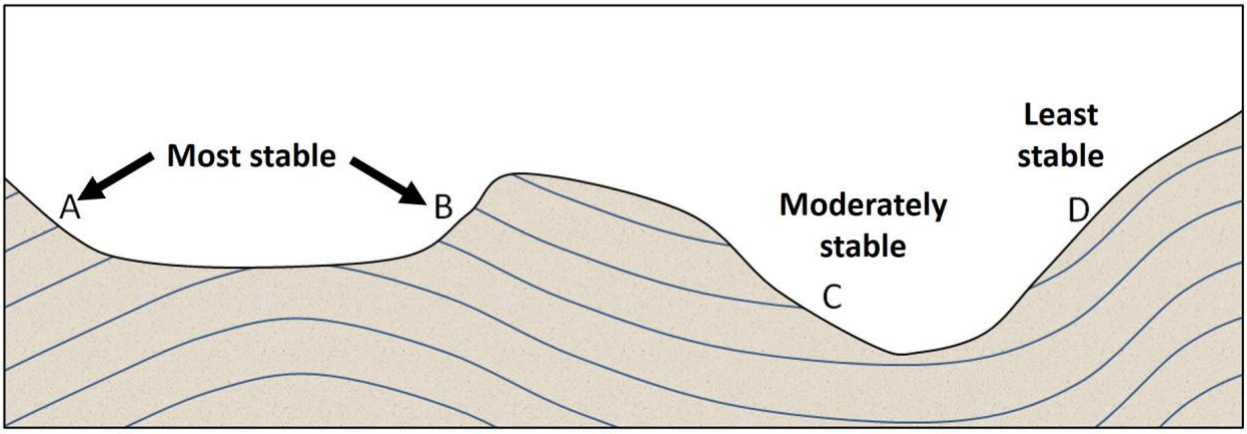


Figure 10.6: Relative stability of slopes as a function of the orientation of weaknesses (in this case bedding planes) relative to the slope orientations.

Water

Slope saturation is a primary cause of mass wasting. A small amount 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. Too much water, however, causes the sand to flow away quickly. 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, encouraging flow.

Landslides 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.

Vegetation

Tree roots, grasses, and other indigenous vegetation can help bind soil together and prevent motion. After a wildfire has ravaged a slope, it is vulnerable to mass wasting and flash flooding during heavy precipitation events.

Undercutting

The process of undercutting occurs naturally along coastlines and river bank; it involves running water or waves removing material from the base of the slope, but not at the top, thereby increasing the slope's angle and the likelihood of slope failure. Undercutting is particularly dangerous when the underlying rock layers slope towards the area.

Ground shaking

An earthquake, volcanic eruption, or even just a truck driving by can shake unstable ground loose and cause a slide. The occurrence of earthquakes in steep landslide-prone areas greatly increases the likelihood that landslides will occur, due to ground shaking alone or **liquefaction**. For example, during the **1994 Northridge earthquake**, more than 11,000 landslides were triggered in the immediate area (10,000 km^2). In volcanic regions, **lahars** and general slope failures are possible. In some cases, **submarine landslides** occur, which may induce **tsunami** waves.

Human Impacts

Humans can contribute to mass wasting in a number of different ways. When an area is under construction, the overall slope must be considered. Construction planners need to consider drainage, loading (addition of weight), undercutting, removal of vegetation, and ground shaking. If the slope becomes compromised, the slope will need to be stabilized before moving forward with construction; however, stabilization does not always prevent future landslides.

Attributions

- Figure 10.5: Derivative of “Forces on a Block on an Inclined Plane” (CC-BY-SA-NC 4.0; Paul Inkenbrandt via Open Geology) by Chloe Branciforte
- Figure 10.6: Derivative of “Slope Stability and Orientation” (CC-BY 4.0; Steven Earle via OpenText) by Chloe Branciforte

Prevention and Awareness

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. 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. 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. It is important to remember that our efforts to "prevent" mass wasting are only as good as our resolve to maintain those preventive measures. For more landslide preparedness visit the **USGS Landslide Preparedness page**.

Activity 10A: Concept Sketches and Mass Wasting

A **concept sketch** is a simplified drawing illustrating the main aspects of landscape or system. It is annotated with concise but complete labels that identify important features. Short sentences describe the processes that are occurring. The final aim is to show the relationships between features and processes. It is not simply a sketch labeled with only the names of features. See a rubric below for what is expected for each success level. Point values will be determined by your instructor.

Skill	Emerging	Progressing	Partial Mastery	Mastery
Identify **Features**	Incomplete labeling.	Some labeling.	Most clearly labeled.	Relevant features clearly labeled.
Identify **Processes**	Incomplete identification and description.	Incomplete identification or description.	Clear identification and description.	Relevant processes clearly identified and described.
Explain **the Connections and Relationships Between Features/Processes**	Incomplete connections/relationships.	Suggests some connections/relationship.	Most connections/relationships highlighted effectively.	Relevant connections/relationships highlighted effectively.
Demonstrate **Proper Use of Terminology**	Incomplete or inappropriate use of terminology/units. Frequent errors and misunderstanding of the subject.	Attempts use of appropriate terminology/units. Some errors and missing components.	Consistent use of appropriate terminology/units. Few errors or missing components.	Consistent and successful use of appropriate terminology/units.
Assess **Scientific Accuracy**	Lacks organization with frequent errors, demonstrating misunderstanding of the subject.	Drawings are readable, with occasional oversimplifications, errors and/or missing components.	Drawings are readable. Consistent use of symbology and/or colors/patterns to illustrate major features and/or processes.	Drawings are clearly readable with accurate details illustrated through appropriate symbols and/or colors/patterns. Sketch shows a scale.

Table 5.3: Rubric for geology concept sketches.

More on Concept Maps is available via NAGT/SERC, Teach the Earth.

1. Draw a concept sketch of the **mass wasting styles**. Labels should be short sentences explaining the relationships between geologic features and processes.

Attributions

Table 5.3: “Concept Sketch Rubric” (CC-BY 4.0; Chloe Branciforte and Emily Haddad, own work)

Activity 10B: Can a House Contribute to 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.

What does a house actually weigh? A typical 150 m^2 (1,600 ft^2) wood-frame house with a basement and a concrete foundation weighs about 145 metric tonnes (319,670 pounds). However, most houses are built on foundations excavated into the ground, which involves digging a hole and removing material, so to accurately determine weight we'd need to subtract the excavated material weight. Let's do that now.

The foundation dug for our example house requires an excavation 15 m by 11 m by 1 m deep.

1. Calculate the volume of "dirt" removed. *Hint: Volume = L x W x H. Show your work.*

   Volume of "dirt" removed =

2. Our "dirt" typically has a density of about 1.6 tonnes per cubic metre (t/m^3). Calculate the weight of the soil that was removed. *Hint: Mass = Density x Volume. Show your work.*

   Weight of "dirt" removed =

3. Which weighs more: the dirt removed to build the foundation, or the house and its foundation?

4. What can you conclude from this comparison?

5. How might a building (house or other) change the drainage on a slope?

Activity 10C: Mass Wasting in California

1. Watch this **video** highlighting mass wasting in Yosemite National Park.
    a. Which mass wasting type is common in Yosemite?
    b. What is one of the likely causes of mass wasting in the park? *Hint: consider the rock type and appearance.*
    c. How does the park geologist determine which boulders are older vs. younger?

2. Navigate to **this USGS page**, and watch a GIF illustrating the Mud Creek landslide which impacted Highway-1 between 2017-2018. What type of landslide does this appear to be?
    a. How can you tell?

3. Open the browser version of Google Earth and fly to 34°21'53.78"N, 119°26'41.90"W. Zoom out to an eye altitude (Camera) of 1,800 ft. What type of mass wasting is this?
    a. How can you tell?

4. This area has experienced two major mass wasting in the last 30 years (1995 and 2005). Does the area appear stable?
    a. Why or why not?

5. Next, fly to Portuguese Bend, CA. You will need to zoom in and out and move along the coast here. Does the area appear stable?
    a. What features or signs support your conclusion.

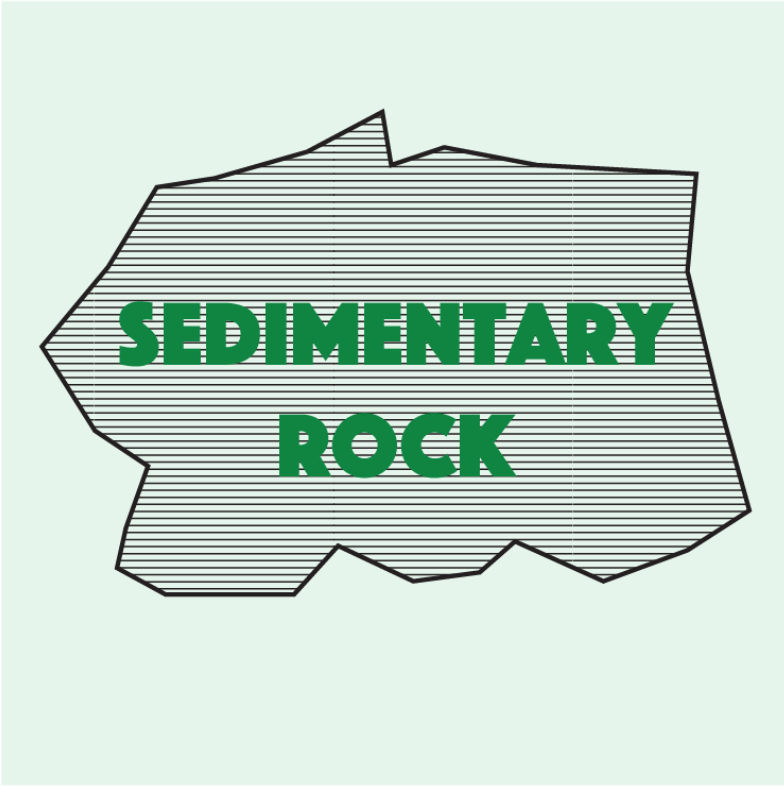
Chapter 11: Sedimentary Rocks

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Describe the processes of weathering, erosion and lithification as they relate to the formation of sediments and sedimentary rocks.
- ✔ Identify sedimentary rocks and their features.
- ✔ Interpret sediments, sedimentary structures and sedimentary rocks to infer potential depositional environments.

Thumbnail for Chapter 11:



Thumbnail: "Sedimentary Rock" (CC-BY 4.0; Emily Haddad, own work)

What Is the Rock Cycle?

The rock cycle is a circular diagram that demonstrates the process by which rocks are continually recycled throughout geologic time. All rocks can be classified into one of three groups: igneous, sedimentary, or metamorphic. This rock classification is based on the origin of each of these rock types, or the processes that form the rock. The Rock Cycle (Figure 11.1), represents the processes that produce each of the rock types. In Chapter 7, we explored igneous rocks, which are produced through the melting of rock and eventual cooling of lava or magma; as cooling occurs, crystals may form. In this chapter, we will investigate sedimentary rocks, which are produced via the processes of weathering (the chemical and physical breakdown of material at Earth's surface that produces sediments), erosion (the movement and deposition of sediments), and lithification (the compaction and cementation of sediments). In Chapter 13, we'll look at metamorphic rocks, which are produced via the agents of change, primarily heat and pressure which typically result in the recrystallization of minerals.

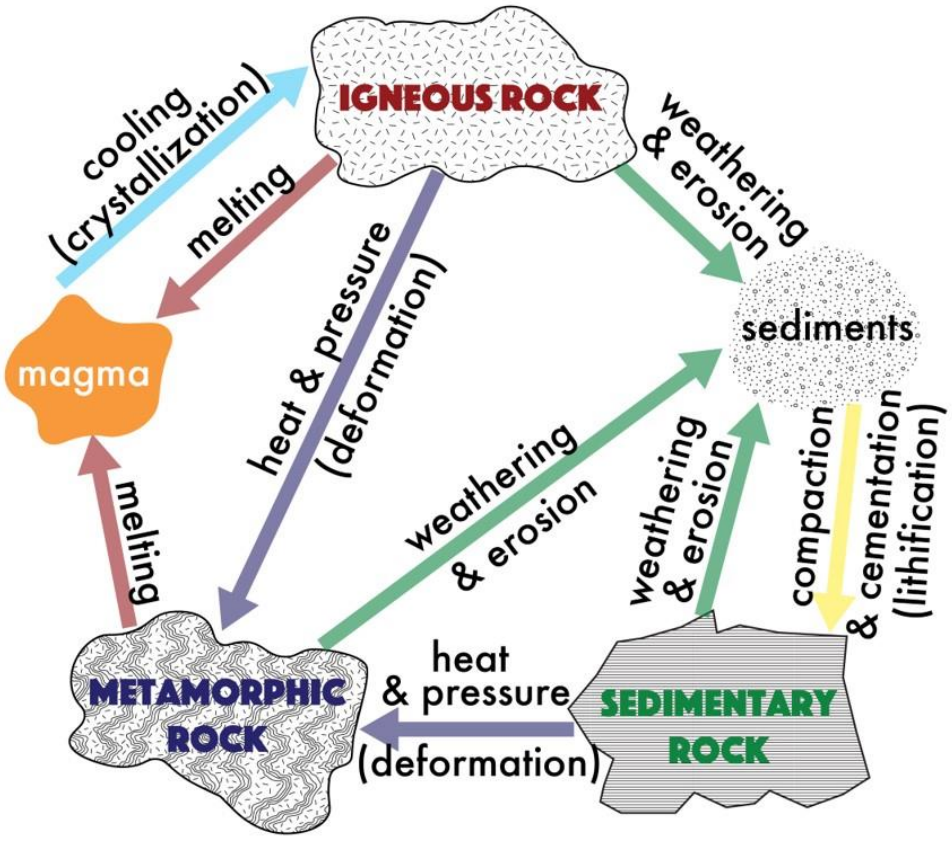


Figure 11.1: The processes of the rock cycle.

Attributions

- Figure 11.1: “Name That Sedimentary Rock” (CC-BY 4.0; Chloe Branciforte, own work)

What Are Sedimentary Rocks and Why Are They Important?

Sedimentary rocks are rocks that form at the Earth's surface via the processes of weathering, erosion, and lithification. They are unique in that they record surface conditions and contain evidence of life, like **fossils**. Sedimentary rocks are the pages in which Earth's history is written and can inform us about a wealth of subjects from the occurrence of ancient catastrophes to the productivity of life.

The identification of sedimentary rocks is more than applying names, since each name is a loaded term that conveys information regarding its history, where it was formed, potentially when it was formed, and the processes that led to its formation. Each sedimentary rock is a puzzle, and by identifying a set of rocks, how they are layered, the fossils contained within, and patterns in the rocks, a geologist can reconstruct an entire environment and ecosystem. Solving these puzzles can be useful to better understand the world around us. Additionally, important mined resources like fossil fuels, water, and salt are typically contained within sedimentary rocks.

Those who study sediments, sedimentary rocks, and their fossils may go by many titles: sedimentologist, sedimentary petrologist, or paleontologist. A sedimentary petrologist is a geoscientist who specializes in sedimentary rocks and their conditions of formation. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including in mining and natural resource extraction. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Weathering

Sedimentary rocks are composed of the broken pieces of other rocks. The obvious place to start is examining how rocks are broken down, in a process called weathering. Weathering is the process from which sediments are derived or produced. There are two categories of weathering. The first, is **physical** or **mechanical weathering**, which results in rocks being physically broken into smaller pieces resulting in an overall size change (imagine hitting a rock with a hammer) (**Figure 11.2**). The second category is **chemical weathering**, which results in a fundamental chemical change of the original rock. The rock becomes altered at the atomic level (imagine dissolving salt in a glass of water). Oftentimes, both physical and chemical weathering will simultaneously affect a rock; however, the extent and rate of weathering is frequently dependent on the environment.

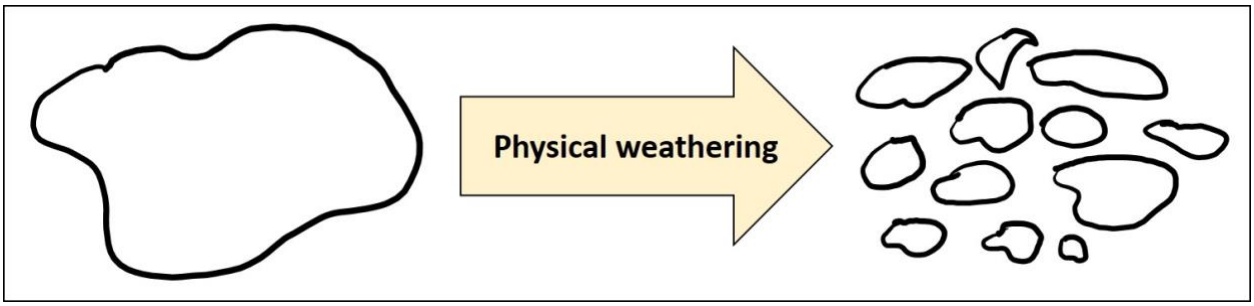


Figure 11.2: Mechanical weathering is the physical breakdown of rock in either size or shape.

Physical or Mechanical Weathering

Abrasion, the most prevalent type of mechanical weathering, results from the collision, breaking, and grinding of rock during the movement of a fluid, either water or air. The size of the carried sediment depends on the fluid type and velocity. A fast fluid (e.g. a rapidly flowing river) can carry large particles and cause large amounts of abrasion. A slow fluid (e.g. a calm stream) would only cause a small amount of abrasion. The density of the fluid also controls the size of particles that can be transported. Denser fluid, like water, can carry larger particles, while less dense fluids, like air, carry smaller particles.

Another common method of mechanical weathering occurs when water seeps into a crack in the rock and freezes; this is called **frost wedging** or **frost heaving**. Water is unique in that it expands when frozen, which puts pressure on the rock and can split boulders (**Figure 11.3**).

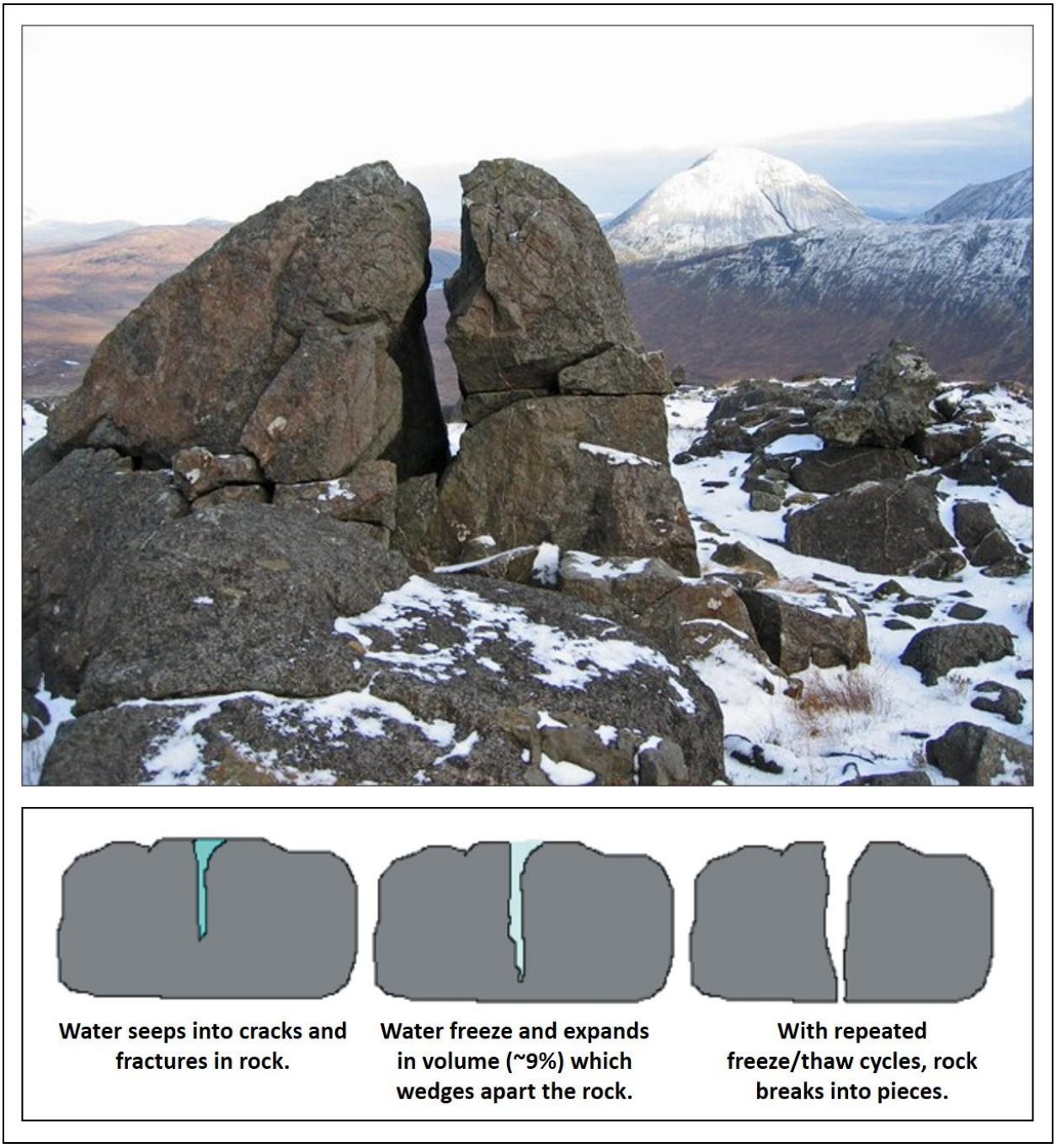


Figure 11.3: *Top,* this boulder in Scotland has been affected by the freeze and thaw cycle resulting in a crack developing. *Bottom,* this image illustrates the step-by-step process of frost wedging.

The addition and subtraction of heat or pressure can also cause rock to break; this is called **exfoliation**. This breakage can also occur with rocks when they cool very quickly or immense pressure is released. Exfoliation of the granite in Yosemite National Park results in many of the rockfalls for which the park is famous (**Figure 11.4**).

Figure 11.4: Exfoliating slabs of granite, on Half Dome in Yosemite National Park, California.

Chemical Weathering

Rocks can be chemically weathered, usually by one of three common reactions. Water is frequently involved as it is good at inducing a chemical change. The first, which you are probably familiar with, is called **dissolution**. In this case, a mineral or rock is completely broken apart in water into chemical ions. These ions are then transported with the water and redeposited as the concentration of ions increases, normally because of evaporation (this is accomplished through a process called chemical **precipitation**, which is different than the rain type of precipitation). **Table 11.1** illustrates the chemistry of calcite, which is prone to dissolution.

Chemical weathering can also change the mineralogy and weaken the original material, again through the agent of water. A mineral can undergo **hydrolysis**, which occurs when a hydrogen atom from a water molecule replaces the cation in a mineral. Typically, this alters minerals like feldspar into a softer clay mineral (like kaolinite).

Thirdly, a mineral can also undergo **oxidation**, which is when oxygen atoms alter the valence state of a cation. This normally occurs on a metal that is freshly exposed to atmospheric oxygen and is commonly known as rusting (**Figure 11.5**). **Table 11.1** illustrates the chemistry of significant minerals and their chemical changes.

Figure 11.5: A freshly broken rock shows differential chemical weathering (probably mostly oxidation) progressing inward.

Chemical Breakdown of Common Minerals		
Chemical change	**Process**	**Chemical reaction**
Pyrite to hematite	Oxidation	$2FeS_2 + 7O_2 + 2H_2O \Rightarrow 2Fe^{2+} + H_2SO_4 + 2H^+$
Pyroxene to iron oxide	Oxidation	$Fe^{2+}SiO_3 + O_2 + H_2O \Rightarrow FeO(OH) + SiO_2$
Calcite to calcium & bicarbonate ions	Dissolution	$CaCO_3 + H^+ + HCO_3^- \Rightarrow Ca^{2+} + 2HCO_3^-$
Potassium feldspar to clay	Hydrolysis	$3KAlSi_3O_8 + 3H_2O \Rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2K^+ + 2OH^-$
Olivine to serpentine	Hydrolysis + Oxidation = Serpentinization	$Fe_2SiO_4 + 4H_2CO_3 \Rightarrow 2Fe^{2+} + 4HCO_3^- + H_4SiO_4$ $2Fe^{2+} + ½O_2 + 2H_2O + 4HCO_3^- \Rightarrow Fe_2O_3 + 4H_2CO_3$

Table 11.1: Common minerals and how they change through chemical weathering.

Chemical and mechanical weathering often work together to increase the overall rate of weathering. Chemical weathering weakens rocks, which makes them more prone to breaking physically, while mechanical weathering increases the surface area of the sediment, which increases the surface area that is exposed to chemical weathering (**Figure 11.6**).

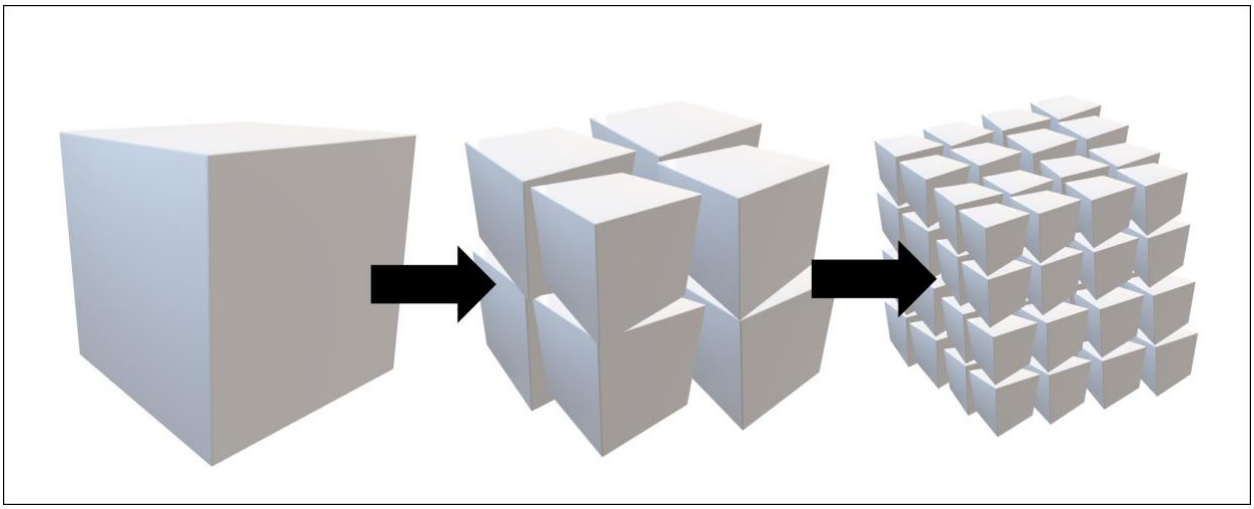


Figure 11.6: When a rock undergoes physical weathering, additional surface area is produced, which can increase the potential for chemical weathering.

Environments with multiple types of weathering typically result in rocks that break down quickly. Humid climates, with abundant water, will generally encourage changes faster than drier climates. In addition, we must also consider the original mineralogy of the rocks, as this can also play an important role in weathering potential (**Table 11.2**).

Finally, biology – plants, animals, and yes, even humans – can cause significant amounts of weathering, sometimes referred to as **biological weathering**. This can be done both physically and chemically. For example, trees put down roots through joints or cracks in the rock and, as the tree grows, the roots gradually pry the rock apart. Additionally, some animals bore into rocks for protection either by force or through the secretion of acid which dissolves the rock. Even bacteria, algae, and lichens produce chemicals that can break down rock.

Relative Stability of Common Minerals Under Weathering		
Mineral Name	**Relative Stability**	**Rate of Weathering**
Hematite	*Most stable*	*Slowest*
Quartz		
Clay minerals		
Muscovite mica		
Potassium feldspar		
Biotite		
Na-Plagioclase feldspar		
Amphibole		
Pyroxene		
Ca-Plagioclase feldspar		
Olivine		
Calcite		
Halite	*Least stable*	*Fastest*

Table 11.2: Common minerals and their stability and associated rate of weathering.

Attributions

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- Figure 11.3: Derivative of “Frost Wedging” (CC-BY 2.0; John Allen via Geograph and CC-BY 3.0; Julie Sandeen via Wikimedia Commons) by Chloe Branciforte
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- Table 11.1: “Chemical Breakdown of Common Minerals” (CC-BY 4.0; Chloe Branciforte, own work)
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- Table 11.2: “Relative Stability of Common Minerals Under Weathering” (CC-BY 4.0; Chloe Branciforte, own work)

Erosion, Transportation, and Deposition

After sediments are produced via weathering, they then undergo erosion. **Erosion** includes both the movement of sediment, **transportation** via the agents of transportation (wind, water, ice, gravity), and the **deposition** of sediment in distinct areas referred to as **depositional environments**.

Sedimentary Depositional Environments

A **depositional environment** is the accumulation of chemical, biological, and physical properties and processes associated with the deposition of sediments that lead to a distinctive suite of sedimentary rocks. Sedimentary environments are interpreted by geologists based on clues within, such as rock types, sedimentary structures, trace fossils, and fossils. Geologists then compare these clues to modern environments to reconstruct ancient environments.

The numerous depositional environments found on earth can be broken into three major categories: 1) **terrestrial or continental environments**, common environments we find on land, 2) **marine environments**, those that are in the ocean, and 3) **coastal or transitional environments**, those at the interface between the first two (**Figure 11.7**).

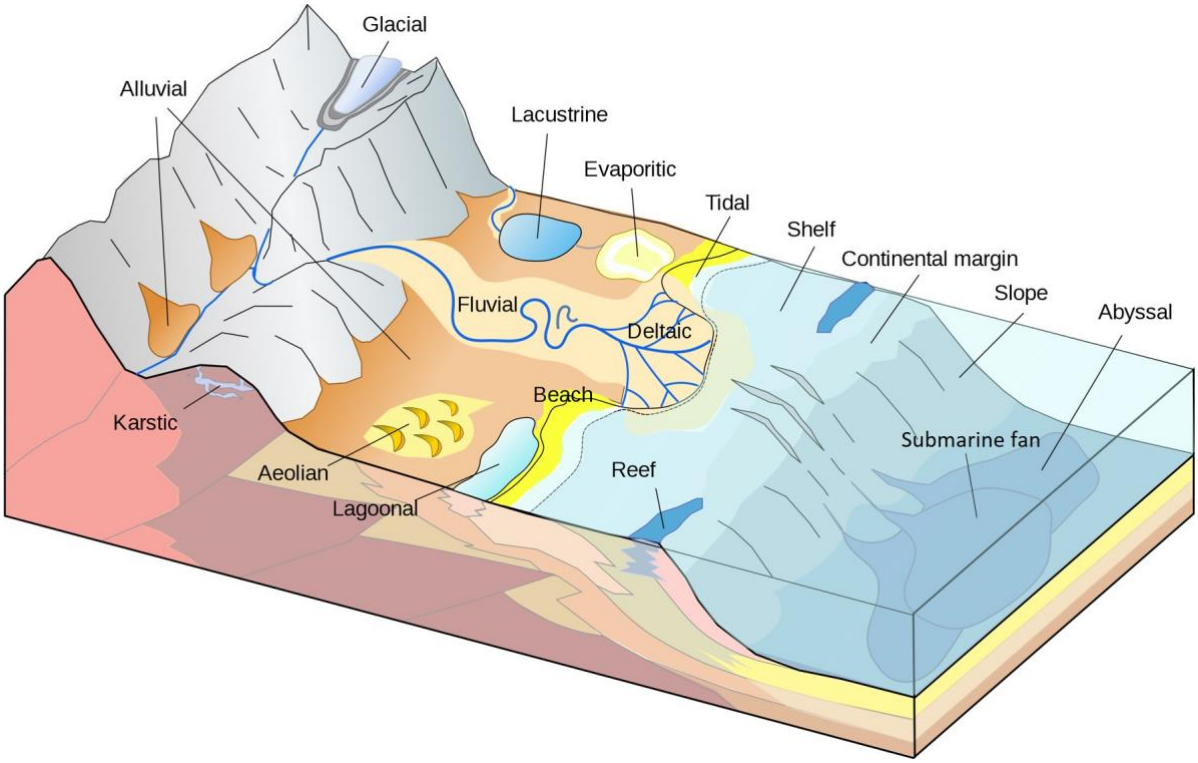

Figure 11.7: Depositional environments within the three major categories, continental, coastal and marine.

Terrestrial (Continental) Environments

There are many different environments on the continents, but consider how they are separated between those that are dominated by the deposition of sediments and those dominated by the erosion of sediments. Erosion occurs in high altitude areas and, although continents are overall topographically elevated compared to the oceans, there are many consistent areas on the continent with distinctive depositional properties. Continental depositional environments are dominated by clastic sedimentary rocks (see the Clastic Sedimentary Rock section), largely because of their proximity to the source of the sediments.

Glacial depositional environments are controlled mostly by the weathering and erosion by glaciers and glacial meltwater. Glaciers most commonly occur in areas that are both high elevation and/or high latitudes. Glaciers are fairly slow moving (centimeters a day) and normally travel short distances from their source, but they can cause immense mechanical weathering. Glaciers grind and bulldoze rock and create piles of poorly sorted sediment called **moraines**. Glaciers also produce a significant though fluctuating amount of meltwater, which flows through the moraines building a system of **braided rivers**. These rivers carry the small sediments further from the end of the glaciers into an area called the outwash plain, which consists of poorly sorted sediment.

Alluvial depositional environments are controlled primarily by gravity, although **ephemeral** river channels may develop during flash flooding. During these flood events extensive sediment will be moved from a high point, generally a mountain range, down to a lower elevation, producing **alluvial fan** deposits. These fan shaped deposits are similar to river deltas but occur on land. The sediment closest to the mountains will be larger in size, with smaller-sized sediment deposited towards the edges of the alluvial fan. Sediment here tends to retain a more angular shape, and little chemical weathering occurs.

Sediments that are deposited through the action of rivers are referred to as **fluvial** depositional environments. The gradient and discharge of a river can greatly control the shape of the river, how it flows, and how it deposits sediment. Rivers alter sediment both chemically and physically as well as sort the sediment since there is a limit to the size or particles a river can carry. Within a **meandering river** we see several different types of sediments, from the pebbles and gravel within the river channel to sandy **point bars** along the outer edge of the meander where the water slows. In addition, we see multiple types of sedimentary structures related to the flow of the river as well as those related to flood events.

We also have sediments deposited within lakes, which are called **lacustrine** depositional environments. Unlike rivers, lakes do not have rapidly flowing water; thus, there is significantly less movement of sediment and smaller particles. The sediment that accumulates in lakes can come from several sources, including rainwater carrying sediment into the lake from the shores, rivers that flow into the lake, and sediment that is transported by the wind. Once the sediment reaches the lake, it remains undisturbed so we see thin layers of fine sediment, with varying amounts of trace fossils.

Lastly, there are **aeolian** depositional environments, which are dominated by currents of wind rather than water. Since air is less dense than water, only smaller particles can be transported. In addition, wind is not restrained within distinctive channels like water and, therefore, the features of aeolian deposits are more widespread than those of fluvial deposits. Certain areas have predominant wind patterns, such that the wind is fairly consistent in direction and strength, which can generate significant sedimentary structures. **Evaporitic** environments are commonly associated in drier climates, where water is only present in the form of seasonal lakes (**playa lakes**) that undergo significant evaporation and sometimes leave behind chemical sedimentary rocks (evaporite deposits). See **Table 11.3** for an overview of these environments.

Characteristics of Terrestrial (Continental) Environments			
Environment	***Transport process(es)***	***Environments***	***Sediment types***
Glacial	Gravity, moving ice, moving water	Valleys, plains, streams, lakes	Glacial till, gravel, sand, silt, clay
Alluvial	Gravity, intermittent moving water	Steep-sided valleys, talus	Coarse, angular fragments
Fluvial	Consistent moving water	Streams	Gravel, sand, silt, organic matter (swamps)
Aeolian	Wind	Deserts and coastal regions	Sand, silt
Lacustrine	Moving water (flowing into lake)	Lakes	Sand (near edges), silt, clay, organic matter
Evaporitic	Moving water (flowing into lake)	Lakes in arid regions (playa lake)	Salts, clays

Table 11.3: Common characteristics of terrestrial environments.

Transitional (Coastal) Environments

The interface between the continents and oceans are complicated areas that can be influenced by rivers, ocean currents, winds, waves, and tides. The sediments of coastal environments are a mixture of materials derived from the continents (clastic and organic) and those from the ocean (chemical and biochemical).

Shorelines that are influenced by strong daily tidal currents are called **tidal mudflat** depositional environments. **Tides** are currents that are the result of the gravitational forces exerted by the moon and the rotation of the earth. Shorelines that have strong tidal currents as well as seafloors with low gradients can have large areas that are submerged during high tide and exposed to air during low tide. These areas often have smaller particles than a normal shoreline since the tidal currents can pull fine-grained marine sediments into the area. In addition, the strong bidirectional currents, daily drying out, exposure to the elements, and abundant life create numerous sedimentary indicators of these environments.

Shorelines that are dominated by ocean currents are called **beach** depositional environments. Shorelines have constant winds blowing on and off shore that are the result of the difference in the way the land and water heat and cool through the day. These winds produce the waves that are iconic at the beach, but as these waves move onto shore they curve, mimicking the shape of the shore, and result in a **longshore current**, which runs parallel to the shore itself. This current carries and deposits sand along the beach. In addition, the wind can also produce dunes, which promote a diverse and complicated ecosystem.

Characteristics of Coastal (Transitional) Environments			
Environment	***Transport process(es)***	***Environments***	***Sediment types***
Tidal	Tidal currents	Tidal flats	Silt, clay
Beach	Waves, longshore currents	Beaches, spits, sand bars, barrier islands	Gravel, sand
Deltaic	Moving water	Deltas	Sand, silt, clay, organic matter (swampy areas only)

Table 11.4: Common characteristics of coastal environments.

Deltaic depositional environments are areas where rivers flow into the ocean, and produce **deltas**. As a river that is carrying material empties into the ocean, the water slows and deposits

sediment. Most of the sediment is deposited at the mouth of the river with some spilling out into the surrounding areas building a distinctive fan of sediment. Since the sediment is coming from the river, the delta is largely a thick sequence of clastic sediment showing indications of the strong flow of the river. See **Table 11.4** for more information regarding these environments.

Marine Environments

Marine depositional environments differ in multiple ways, but the resultant rocks are primarily controlled by the proximity and supply of continental sediment, the water depth, and the community of organisms that live in the area. The further an environment is from the shore, the less clastic sediment will be present, and the area will have a higher concentration of the chemical and biological sedimentary rocks that are formed within the ocean. In addition, some organisms in the right environmental conditions can produce huge amounts of skeletal material.

Shallow marine depositional environments are areas that are close to shore, but always submerged. These areas have a significant amount of mature clastic sediment along with marine algae (like seagrass) as well as skeletal material from animals like coral, echinoderms (sea urchins, sand dollars, sea stars), and mollusks (clams and snails). These areas can have a significant variation in their energy level, from high-energy shallow areas influenced by waves to low-energy deeper areas only influenced by large storms. A better understanding of the relative water depth can often be determined in sedimentary rocks based on their sedimentary structures, in addition to the community of organisms and types of trace fossils found in the rock, since these can be very sensitive to depth.

In warm tropical shallow water, we often find **reef** depositional environments. Reefs are formed through the growth of coral colonies building a large three-dimensional structure with their calcite skeletons. Corals can grow in many different marine environments, but they can only produce reefs when their symbiotic algae that live within their tentacles are able to photosynthesize effectively, resulting in more energy for the coral to grow faster. Reefs also create a barrier between shallow water environments and ocean currents, producing shallow, low-energy environments called **lagoons**. These **lagoonal environments** have thin layers of fine sediment that we would expect in quiet water along with chemical sedimentary deposits that are the result of evaporation.

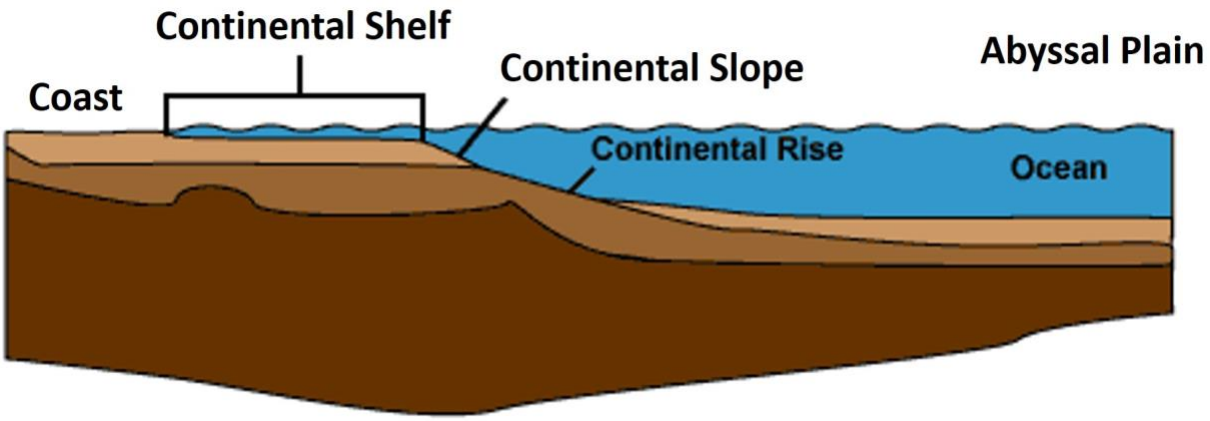

Figure 11.8: The continental shelf to abyssal plain.

Most of the ocean consists of **deep marine** depositional environments. **Turbidite flows** are fast-moving currents carrying a variety of sediment sizes down the **continental slope** to the **abyssal plain** (**Figure 11.8**). As the current slows, it can no longer carry the largest particles, so these will be deposited first. As the current continues to slow, progressively smaller particles are deposited on top of the bigger particles, forming **submarine fans** with **graded bedding** (**Figure 11.9**).

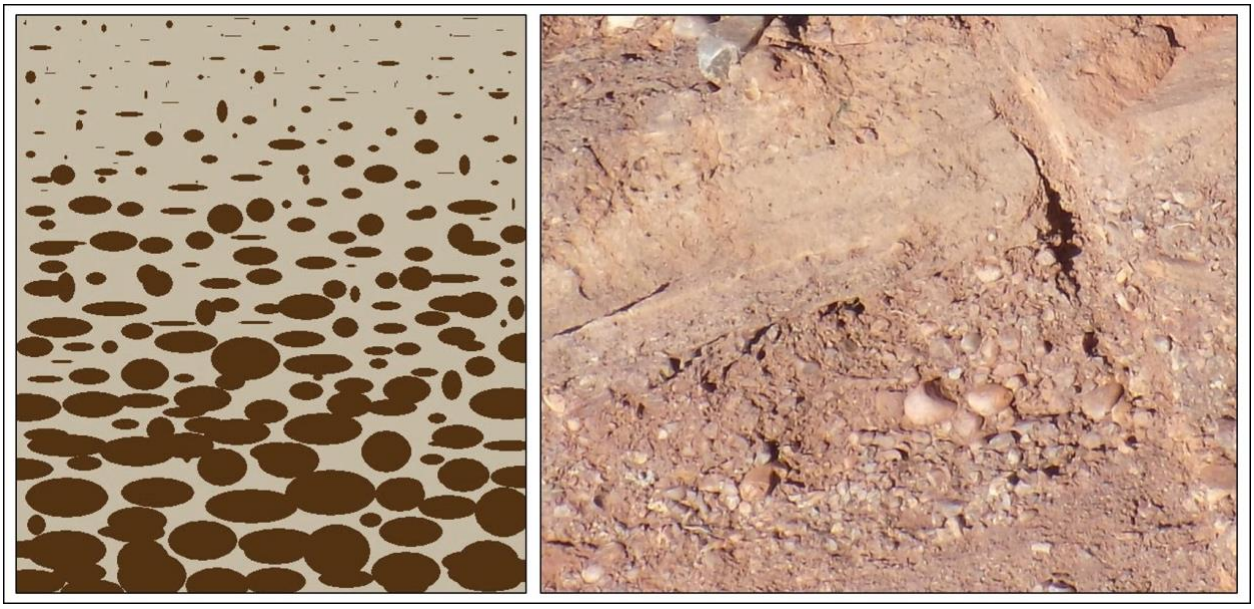

Figure 11.9: Left, grain size distribution in graded bedding, notice the fining upward sequence. Right, turbidite deposit from Santa Barbara County.

The remainder of the deep ocean contains areas beyond the reach of most clastic sediment other than the dust carried by the wind (red clay deposits). Therefore, sediment within the

deep ocean is primarily produced chemically and biologically. The largest source of sediment in these deep settings is skeletal material from some of the smallest marine organisms (carbonate and siliceous oozes). Multiple types of single-celled organisms can produce shells composed of either silica or calcite. These shells are mostly produced in the surface waters that are bathed in sunlight permitting photosynthesis. When these organisms die, the shells then rain down into deeper water; this slow accumulation of sediment produces fine layers of biochemical sedimentary rocks. In some cases, these shells are dissolved or altered before they reach the bottom (which can be miles away) and are precipitated as chemical sedimentary rocks. Obviously, there is not a clear boundary between shallow and deep-water environments given the gradient of the ocean floor; however, deep marine depositional environments are normally thousands of feet deep and beyond the influence of even large storms. See **Table 11.5** for more information regarding these environments.

Characteristics of Marine Environments			
Environment	***Transport process(es)***	***Environments***	***Sediment types***
Shallow marine water	Waves and tidal currents	Continental shelves and slopes, lagoons	Carbonates in tropical climates, sand/silt/clay elsewhere
Reefs	Waves and tidal currents	Reefs and adjacent basins	Carbonates
Lagoonal	Little transportation	Lagoon bottom	Carbonates in tropical climates
Submarine fan	Underwater gravity flows (turbidity currents)	Continental slopes, abyssal plains	Gravel, sand, silt, clay (turbidites)
Deep marine water	Ocean currents	Deep-ocean abyssal plains, trenches	Clay, carbonate mud (carbonate ooze), silica mud (siliceous ooze), red clays

Table 11.5: Common characteristics of marine environments.

Attributions

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- Table 11.3: “Characteristics of Terrestrial Environments” (CC-BY 4.0; Chloe Branciforte, own work)
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- Figure 11.8: Derivative of “Continental Shelf” (Public Domain; Interiot via Wikimedia Commons) by Chloe Branciforte
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- Table 11.5: “Characteristics of Marine Environments” (CC-BY 4.0; Chloe Branciforte, own work)

Lithification

The transformation of sediments into sedimentary rock happens during **lithification**. As sediments accumulate in the depositional environments, they are buried under more and more sediment. The sediments begin to compact under their own weight. **Compaction**, the squishing, of sediments, causes migration of water with dissolved ions. These ions become a natural glue, called **cement**, which precipitates and sticks sediments together, in a process called **cementation**. Types of cement include carbonate (calcite), iron-oxide (hematite), and silica (quartz). Compaction and cementation must both occur for a sedimentary rock to form; without lithification, the sediment will not transform into a true rock (**Figure 11.10**).

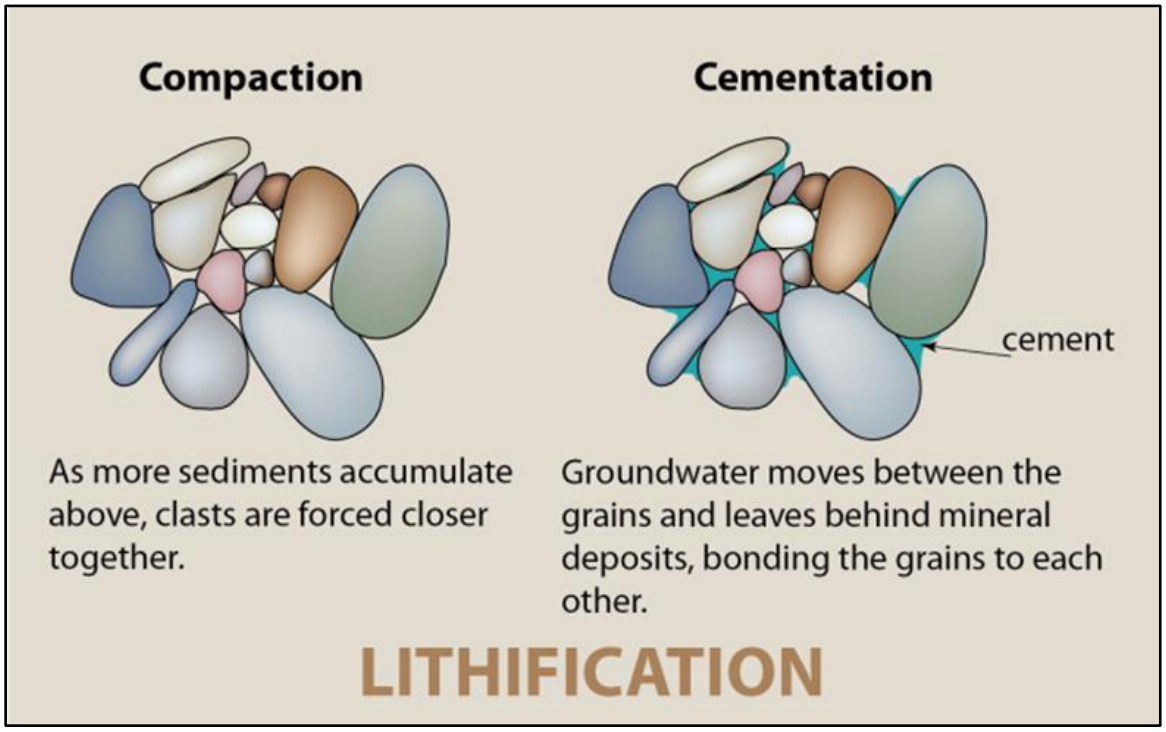

Figure 11.10: Lithification turns sediments into solid rock. Lithification involves the compaction of sediments and then the cementation of grains by minerals that precipitate from groundwater in the spaces between these grains.

Attributions

- Figure 11.10: Derivative of “Lithification” (CC-BY 4.0; Karla Panchuk via OpenTextBC) by Emily Haddad.

Sedimentary Structures

Sedimentary rocks often show distinctive patterns, called **sedimentary structures**, that reflect events or conditions during deposition. These patterns in the rocks can be very informative to geologists attempting to reconstruct the environment in which a sedimentary rock was formed. Many sedimentary structures are useful as "up-indicators", meaning geologists use them to interpret where the surface of the Earth was in the geologic past. This is particularly useful if the layers have been deformed, bent or broken through tectonics.

Most students are familiar with ripples and dunes (mega-ripples). We would typically see these structures at the beach or in deserts. Ripples and dunes form as a result of a wind or water current. **Current or asymmetric ripples** form when a dominant current, which moves in one direction, is present. The current pushes sediment into a pile: on the down-current side the sediment is shadowed and protected from the wind or water current; however, erosion on the up-current side results in a shallow slope and deposition on the steeper, down-current side. If you cut a ripple or dune in half and look at it in profile, you will see inclined layers of sediment building up on the steep down current side of the ripple (**Figure 11.11**).

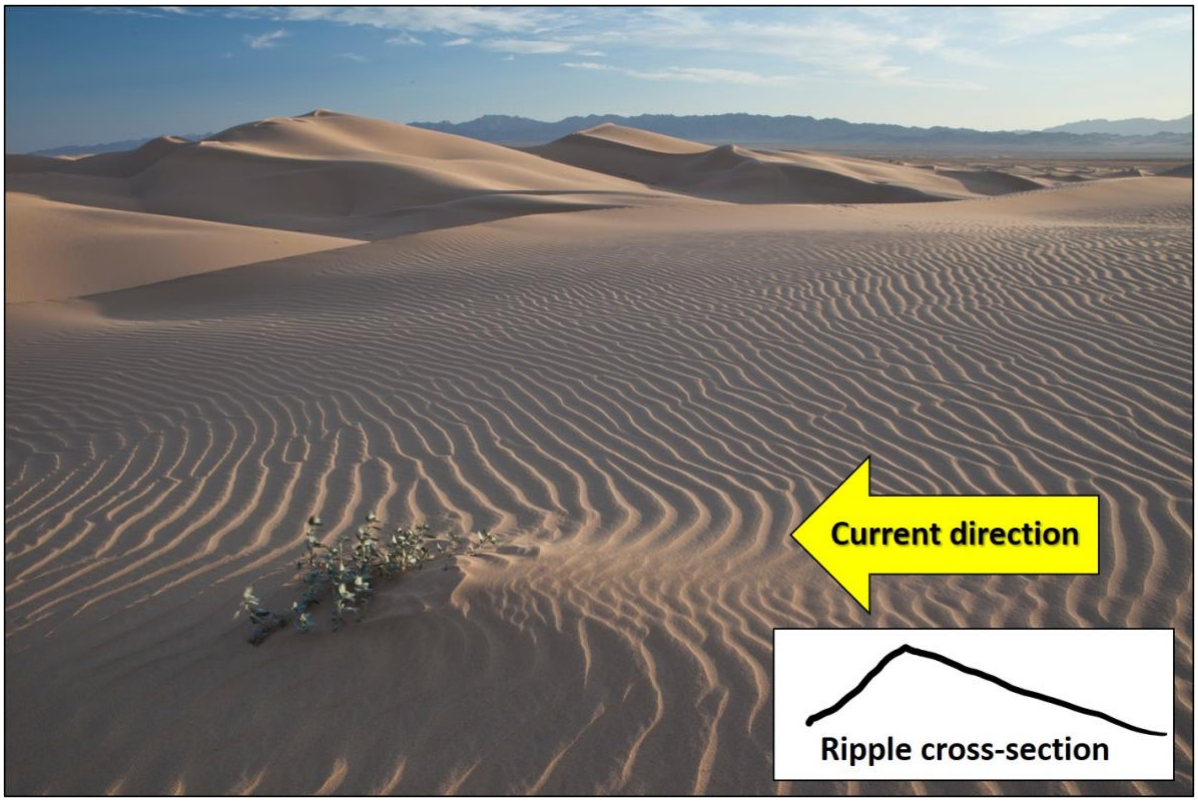

Figure 11.11: Modern current ripples forming in Cadiz Dunes Wilderness area in San Bernardino County. *Bottom inset image:* a cross-section of an asymmetric ripple. In both images the dominant current (wind) moves from right to left.

We often see multiple layers of beds consisting of these inclined layers, called **cross-beds**, which represent multiple generations of migrating ripples or dunes. Both ripples and cross-beds indicate the presence and direction of the current in an environment (**Figure 11.12**). Visit this site to see cross-beds on a sample from the Precambrian Johnnie Formation in southeastern Death Valley.

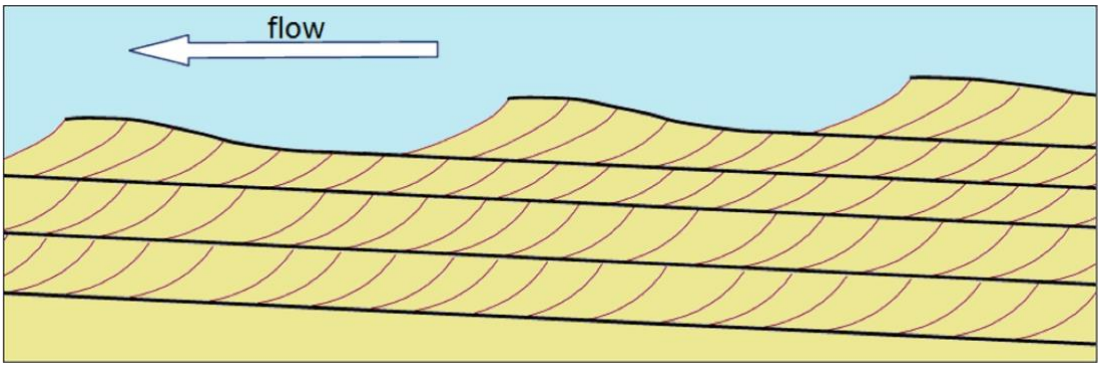

Figure 11.12: Formation of cross-beds as a series of ripples or dunes that migrate with the flow. Each ripple advances forward (right to left in this view) as more sediment is deposited on its leading face.

Wave-formed, symmetric, or oscillation ripples are commonly found in shallow waters, beaches, or tidal flats where water oscillates back and forth with wave-action. In cross-section, these ripples are symmetric and have long relatively straight crests (**Figure 11.13**).

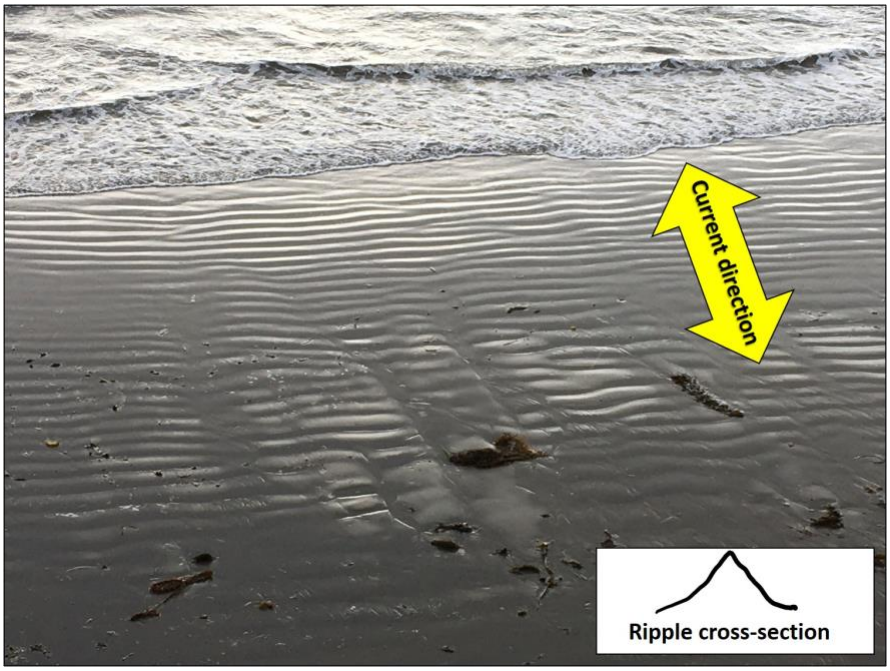

Figure 11.13: Modern oscillation ripples forming near the Ventura Pier in Ventura, California.

Mud cracks, covered and preserved cracks that are the result of the drying of wet mud, and **raindrop impressions**, covered and preserved impacts of raindrops in soft mud, are both sedimentary structures that inform us about the sediment, water content, and exposure at the surface above water level.

Some sedimentary structures indicate changes in the strength of a current. Imagine a fast-moving current carrying a variety of sediment sizes; if the current slows, it will no longer be able to carry the largest particles and they will be deposited first. Then, as the current continues to slow, progressively smaller particles are deposited on top of the bigger particles, forming a sedimentary deposit called a **graded bed**. This graded bed is a sedimentary layer with larger clasts on the bottom and smaller clasts on the top. These types of beds can be the result of floods in a river, storms in the ocean, or **turbidite flows**.

Related to sedimentary structures are **trace fossils**, which are patterns in the rocks that are caused by the activity of organisms. Trace fossils indicate different aspects about the environment depending on the trace and the identity of the tracemaker. Traces can be terrestrial (e.g. footprints, burrows or dens, or the traces of roots) and can inform us about the climate, ecosystem, and the development of soils. Traces can also be found in freshwater and marine environments (e.g. burrows, borings, footprints, or feeding traces) and tell us about the sediment, chemistry of the pore water, and the life that lived within it. Visit this site to see trackways from the Pliocene of Death Valley National Park.

Attributions

- Figure 11.11: Derivative of “Cadiz Wilderness and Valley” (Public Domain; Bob Wick/BLM via Flickr) and “Current Ripple” (CC-BY 4.0; Chloe Branciforte, own work) by Chloe Branciforte
- Figure 11.12: “Cross-bedding” (CC-BY 4.0; Steven Earle via OpenTextBC)
- Figure 11.13: “Oscillation Ripple” (CC-BY 4.0; Chloe Branciforte, own work)

Clastic Sedimentary Rocks

How Do I Recognize a Clastic Sedimentary Rock?

Sedimentary rocks can be subdivided into two major groups based on the processes responsible for their formation: clastic (detrital) sedimentary rocks and **non-clastic sedimentary rocks**. Non-clastic (chemical, organic, biochemical) rocks are determined by their major chemical composition; however, if the sedimentary rock is composed of the broken pieces of other rocks, largely produced via physical weathering, the rocks are referred to as **clastic or detrital sedimentary rocks**. In a clastic sedimentary rock, the classification will primarily focus on the clast properties, including the clast size, overall shape (well-rounded to angular), and sorting of the clasts within the rock (uniform clast size to a range of sizes) (**Figure 11.14**).

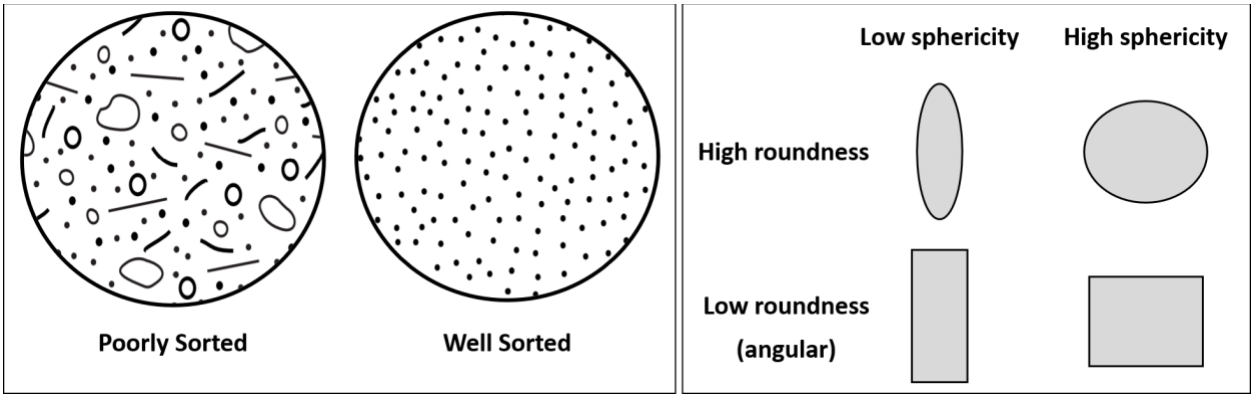

Figure 11.14: *Left,* comparison between poorly sorted and well sorted sediments. *Right,* comparison between sphericity and roundness of sediment grains.

Recall that weathering and erosion generally occur in areas of high elevation, such as the mountains, while deposition occurs in lower areas such as valleys, lakes, or the ocean. Sediment is transported to the area of deposition via the **agents of transportation**: ice, water, air or gravity. During transportation, sediment changes, often significantly. Geologists (and you!) can recognize the amount of change and the distance the material has traveled, and the transport mechanism, by looking at the maturity of the sediment. **Sediment maturity** refers to the size, shape, and the general mineral composition of the sediment.

The size of sediments can be described using three broad categories: gravels, sands, and muds (**Figure 11.15**). Gravels and sands are visible, whereas muds are too small to see with the naked eye and typically need magnification to distinguish individual clasts.

The further sediments travel from their original source, the smaller, more **rounded**, **sorted**, and **uniform** they become (**Figure 11.16**). Consider your own life or educational journey: the more experiences you collect, the more well-rounded you become. For example, prior to graduation, most community colleges require you to complete numerous general education courses; this requirement is to facilitate your development, much like weathering and erosion, and to help you become a more well-rounded student and person. Secondly, much like each of us, our differences are in part a result of our experiences. The differences of clastic rocks are related to the various depositional environments, and these environments, and the distance traveled, can be interpreted based on the characteristics of the sediment.

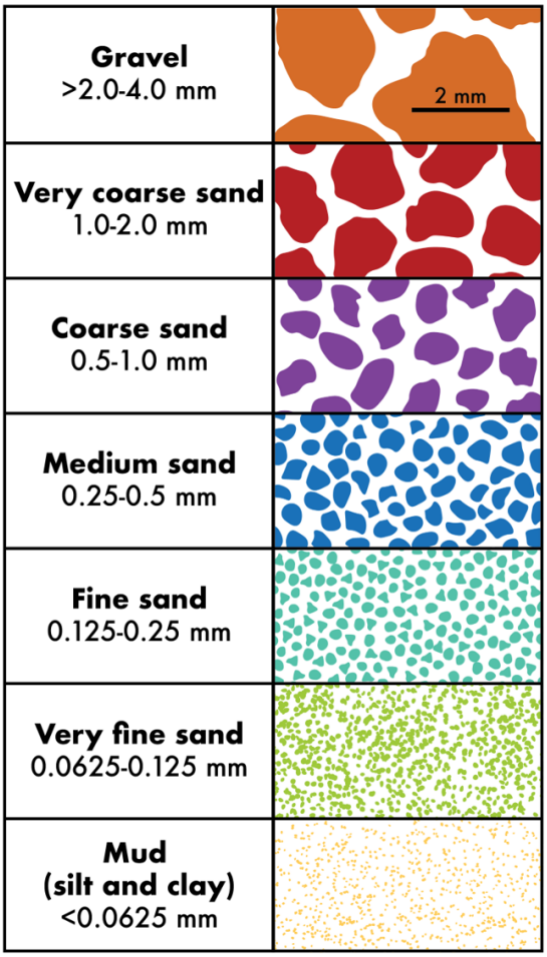

Figure 11.15: To characterize sediments by size, geologists utilize qualitative and quantitative descriptors.

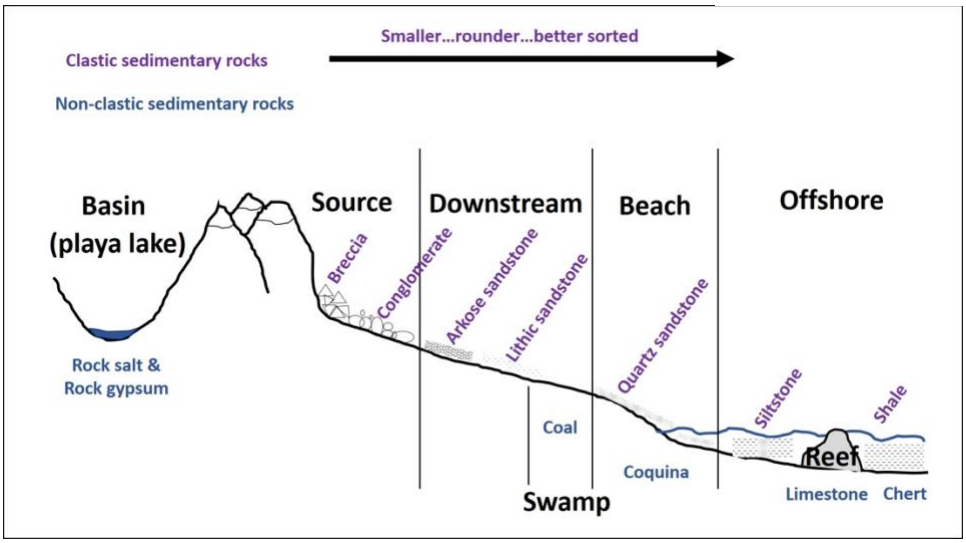

Figure 11.16: As sediment moves through different depositional environments it is altered and changed to reflect those environments.

Identifying the Different Clastic Sedimentary Rocks

Sedimentary breccia is an immature sedimentary rock with a poorly sorted mixture of clay, sand, and angular pebbles (gravel-sized) (**Figure 11.17**). The mineralogy of the clasts (sand and pebbles) often varies depending on the original source rock. Sedimentary breccias are typically found in continental environments, such as ancient landslides, or alluvial fans. The poorly-sorted, and angular nature of the gravel indicates the rock has only been transported a short distance, likely via gravity or inconsistent water.

Figure 11.17: Breccia is a poorly sorted rock with large, angular grains.

Conglomerate is an immature sedimentary rock, with a poorly sorted mixture of clay, sand, and rounded pebbles (gravel-sized) (**Figure 11.18**). The mineralogy of the clasts (sand and pebbles) varies depending on the original source rock. Conglomerates are typically found in continental environments, such as ancient landslides, alluvial fans, or pebble beds in rivers. The poorly-sorted nature of the gravel indicates the rock has only been transported a short distance, but the rounded grains suggest some transportation, generally via a consistent water source.

Figure 11.18: Conglomerate is a poorly sorted rock with large, rounded grains.

A **sandstone** consists of sand-sized clasts and is typically gritty to the touch (think about how sandpaper feels). These clasts vary in shape and mineralogy. Some sandstones may contain many minerals, while others may contain only quartz. Certain sandstone varieties, like arkose, are relatively immature and typically have more angular, moderately sorted, sand grains composed dominantly of the

feldspar minerals (**Figure 11.19**). **Arkose sandstone** is typically associated with continental environments, like alluvial fans. **Quartz sandstone** is mature, as it contains well-rounded, well-sorted pure quartz grains. Quartz sandstone is typical of continental and transitional environments, like desert dunes or beaches. **Lithic sandstones** contain an abundance of lithic (rock) clasts. The **ternary diagram** in **Figure 11.19, right**, allows a sedimentary petrologist to carefully classify a sandstone based on its mineral composition.

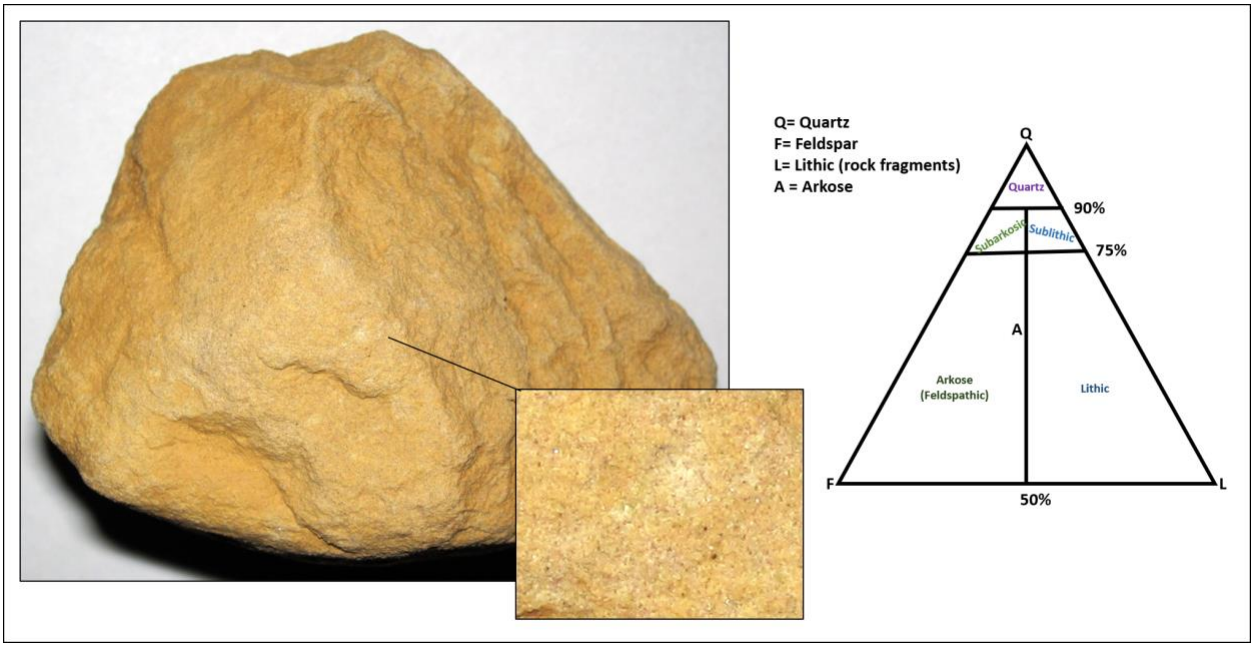

Figure 11.19: Sandstone is composed of sand-sized grains. The ternary diagram to the right, illustrates the various sandstone types, which are determined based on the overall mineral assemblage of the sandstone.

Mudrocks, which are composed of varying amounts of silt or clay-sized particles, include a number of different named rocks. Silts and clays are very small and will likely need magnification to be visible, perhaps beyond what your hand lens can provide. In general, silts may feel slightly gritty; a good test for this in the field is to rub the rock gently on your front tooth. Your teeth are surprisingly sensitive, and will pick up the slight grit of a silt in a **siltstone**. If the rock is a **mudstone** or **shale** (contains layering, or fissility), the rock will contain dominantly clay-sized sediment

Figure 11.20: Shale is composed of primarily mud-sized grains.

and will feel smooth to the touch and on your tooth (**Figure 11.20**). Should you want to try this with your samples, check with the instructor first. Overall, mudrocks are extremely mature, and are made from the smallest particles, carried by wind or barely moving water. Silt and clay-sized sediment are typically thousands of miles from their original source rock.

Attributions

- Figure 11.14: Left, “Sediment Sorting” (CC-BY 4.0; Chloe Branciforte, own work); Right, “Sediment Sphericity and Roundness” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 11.15: “Sediment Grain Size” (CC-BY 4.0; Emily Haddad, own work)
- Figure 11.16: “The Journey of Sediment” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 11.17: “Chert Breccia” (CC-BY 2.0; James St. John via Flickr)
- Figure 11.18: “Quartz Pebble Conglomerate” (CC-BY 2.0; James St. John via Flickr)
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- Figure 11.20: “Gray Shale” (CC-BY 2.0; James St. John via Flickr)

Non-Clastic Sedimentary Rocks

How Do I Recognize a Non-Clastic Sedimentary Rock?

If the sedimentary rock is the product of chemical weathering, it will be referred to as **non-clastic sedimentary rock**, an all-inclusive term which covers sedimentary rocks produced via chemical, biochemical or organic processes. In a non-clastic rock, the classification is based primarily on the composition of the material and how it developed.

Chemical and Biochemical Sedimentary Rocks

In general, chemical sedimentary rocks typically have a crystalline appearance and form through the inorganic precipitation of minerals from a fluid. If the ions present within a fluid (water) become very concentrated, either by the addition of more ions or the removal of water (by freezing or evaporation), then crystals begin to form. In this case, identification of the type of sedimentary rocks is based on the minerals present.

In biochemical rocks, organisms typically facilitate the precipitation of these minerals from water. An example of biochemical precipitation is the formation of skeletal minerals in many organisms: from starfish and clams that grow calcite, to sponges that grow silica-based material, to humans that have bones and teeth made of hydroxyapatite. In many cases, it is hard to differentiate whether a mineral was formed organically or inorganically. Organic sedimentary rocks are those formed mostly from carbon-based organic material produced by ancient life.

Carbonate Sedimentary Rocks

Carbonates are one of the most important groups of sedimentary rocks. They can result in distinctive landscapes, called karst topography (more on this in Groundwater) and human hazards like sinkholes.

Limestone, one of the most abundant sedimentary rocks, is composed of the carbonate mineral calcite. If you remember our mineral unit, calcite undergoes dissolution in acids, and will bubble, fizz or effervesce, when dilute HCl is applied (**Figure 11.21**). There are many varieties of limestone and all vary greatly in appearance; however, all varieties will fizz

Figure 11.21: Calcite reacting (bubbling) with the addition of dilute (1M) hydrochloric acid (HCl).

or bubble when dilute HCl is applied. Limestone can form inorganically from a supersaturation of calcium and carbonate ions in water in a range of environments from caves to tropical beaches, although most limestone is marine in origin.

Crystalline limestone (micrite) is typically inorganic in nature and consists of crystals of calcite or microcrystalline masses of calcite (**Figure 11.22**). It can be light gray to darker gray in color and the calcite crystals will sparkle when the sample is moved around under a light. Typically, crystalline limestone is indicative of a deep marine environment, but there are also lacustrine crystalline limestones.

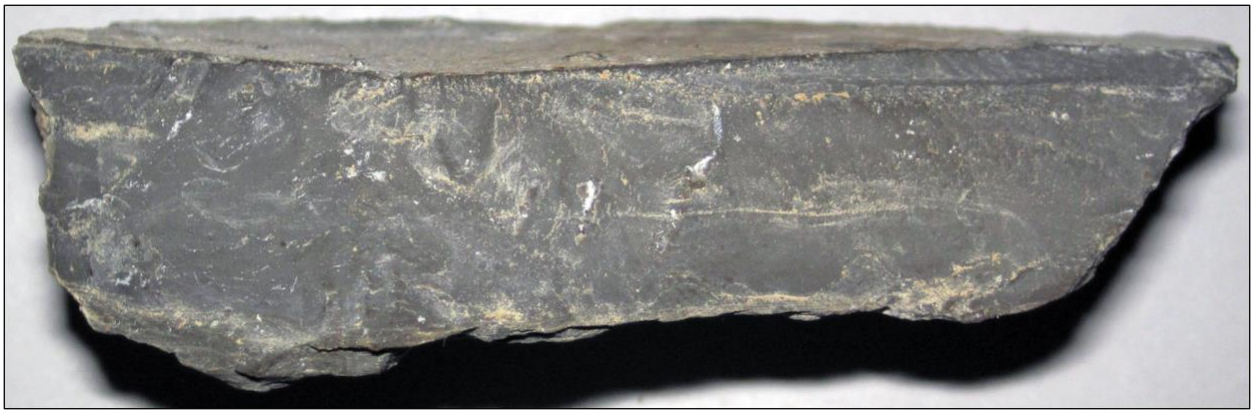

Figure 11.22: Micrite limestone is composed entirely of crystalline calcite.

Coquina often has a biologic component and is composed exclusively of shell or coral fragments (sometimes referred to as shell hash). Coquina looks a bit like dried oatmeal or a granola bar (**Figure 11.23**).

Figure 11.23: Coquina is composed entirely of shell hash (finely-busted up seashells).

Fossiliferous limestone will contain fossils, but unlike coquina will not be entirely made of fossils. Oftentimes, between the fossils there will be calcite-rich mud (**Figure 11.24**). Typically, the fossils are marine in origin and include shells, crinoids, or other invertebrate marine life.

Figure 11.24: Fossiliferous limestone contains an abundance of fossils but is not entirely composed of them. Typically, the areas between the fossils are composed of limey muds, which also react with HCl.

Oolitic limestone is composed of **ooids** (a fun geology word!), small calcite spheres that typically form in shallow, warm, highly agitated marine environments (**Figure 11.25**).

Figure 11.25: Oolitic limestone with ooids, rounded spheres of calcite.

Chalk also has a biochemical origin and is made entirely of the small tests (shells) of marine organisms called coccolithophores, or coccoliths for short. These organisms are incredibly small, and can only be viewed under extreme magnification (**Figure 11.26**). Remember writing with chalk on a chalkboard? This rock will be powdery and leave a mess on your hands.

Figure 11.26: Chalk limestone, with a close-up of a single coccolithopore.

Travertine and **tufa** are both unique limestone varieties as they form in terrestrial (continental) environments. Travertine is commonly associated with hot spring environments, where supersaturated alkaline waters are geothermally heated (**Figure 11.27**).

Figure 11.27: Travertine limestone with vugs (openings or holes).

The most famous hot spring travertine deposits are from Italy. Here in the US, the largest deposits are located in Mammoth Hot Springs in Yellowstone National Park. In California, Lassen Volcanic National Park has smaller deposits of travertine. Travertine can also be associated with caves and speleothems. Tufa commonly forms when carbonate minerals precipitate out of ambient temperature water, usually water that has not been geothermally heated. Here in California, there are beautiful tufa spires in Mono Lake and the Trona Pinnacles (**Figure 11.28**).

Figure 11.28: The Trona Pinnacles, located in San Bernardino County, are a collection of 500 tufa spires rising from the bed of the Searles Dry Lake basin. These tufa spires, some as high as 140 feet, were formed underwater 10,000 to 100,000 years ago, when Searles Lake, and other Pleistocene lakes, existed between Mono Lake and Death Valley.

Dolostone is made from microscopic crystals of the mineral dolomite (**Figure 11.29**). Although also a carbonate mineral, dolomite only weakly reacts to dilute HCl. You must scratch and powder dolostone to increase the surface area to see the reaction with acid. Even after all that work, the reaction is muted (and underwhelming) when compared with calcite's reaction. Dolostone typically forms through the inorganic chemical alteration of a limestone and is therefore a chemical rather than biochemical sedimentary rock.

Figure 11.29: Dolostone which contains the mineral dolomite. Most dolostones are chemically altered limestones.

Siliceous Sedimentary Rocks

Chert is composed of microcrystalline varieties of quartz, and thus it has properties that are associated with quartz itself, such as conchoidal fracturing and hardness greater than glass (**Figure 11.30**). Typically, cherts are identified based on their appearance; for example, jasper is often red chert, flint is gray chert, and agate are banded cherts. Chert typically forms in deep marine environments from siliceous material that is either inorganic (silica clay) or biologic, a siliceous ooze formed from the skeletons of sponges and single-celled organisms like diatoms and radiolarians. Chert may also form petrified woods; these cherts form due to chemical changes during the heat and pressure of burial (diagenesis). Deep marine chert can be bedded or found as nodules in limestone layers. In prehistoric times, chert was often used for the construction of tools, like blades, where obsidian (volcanic glass) was unavailable.

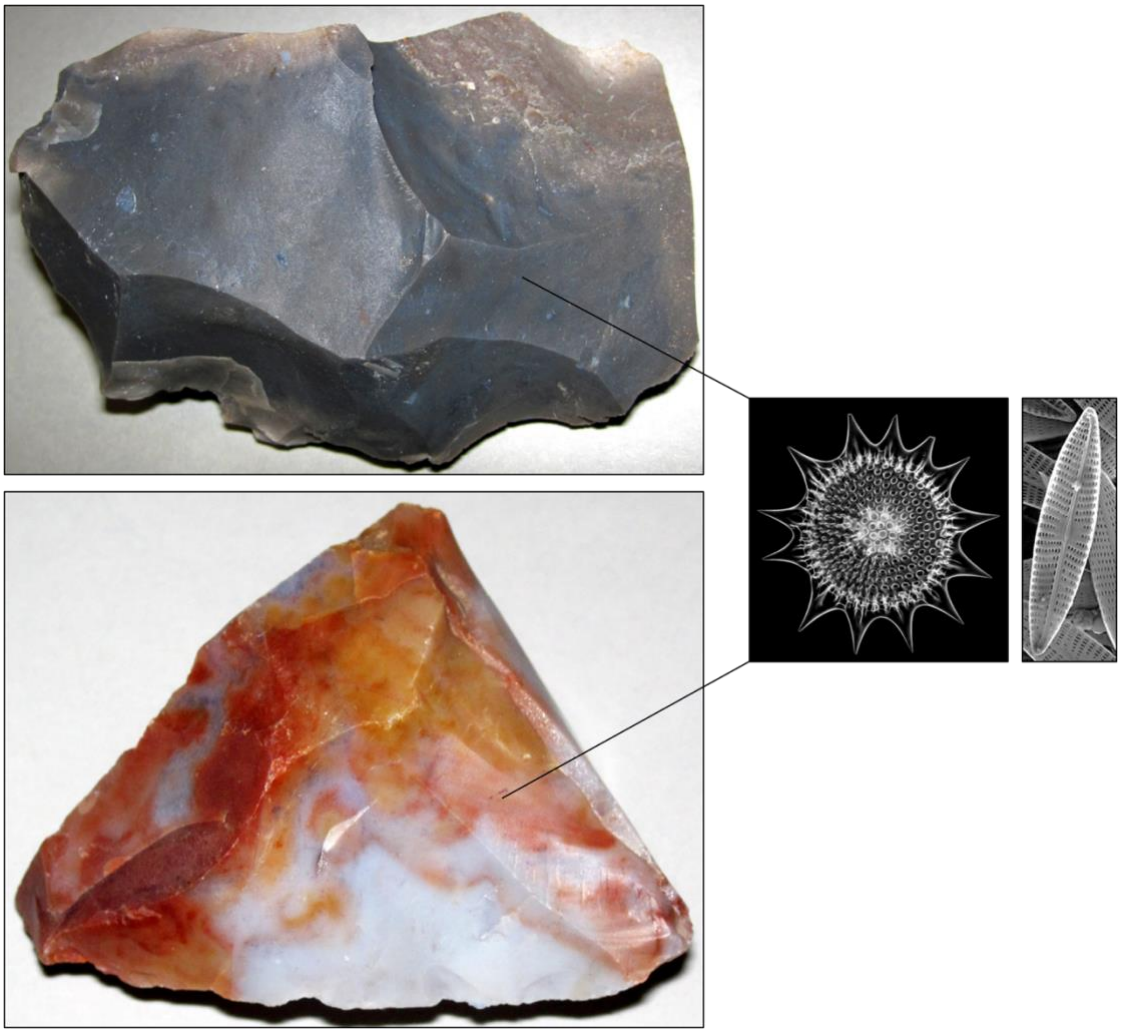

Figure 11.30: Chert, a hard sedimentary rock, will often show conchoidal fracture or sharp edges. Most deep marine cherts will be composed of siliceous single-celled organisms, like radiolarians and diatoms.

Evaporite Sedimentary Rocks

Evaporites are formed via the precipitation of minerals from the evaporation of water, in either restricted marine basins, playa lakes, or salt flats, like those of Death Valley, CA (**Figure 11.31**). Many of the evaporite deposits in California are geologically young. **Rock salt**, an aggregate of the mineral halite, may retain its cubic form and will vary in color. **Rock gypsum** (gypstone), an aggregate of the mineral gypsum, will typically be soft and may be massive or fibrous in appearance. Many of the evaporites contain significant economic minerals; for example, salt domes can be important in the search for petroleum.

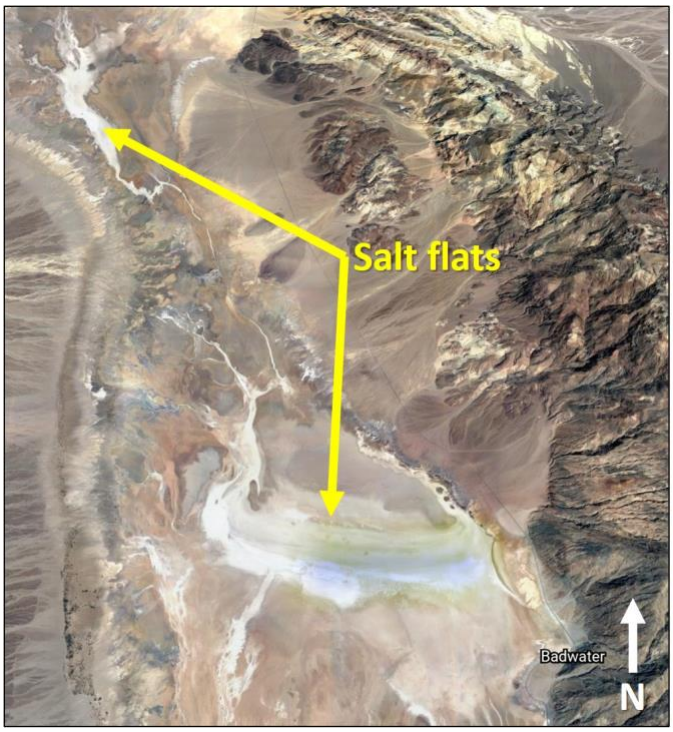

Figure 11.31: Evaporite minerals compose the salt flats of Badwater Basin, Death Valley.

Organic Sedimentary Rocks

Organic sedimentary rocks are rocks that consist mostly of organic carbon and are associated with significant biological activity. Other sedimentary rocks, such as limestone and shale (like oil shale) can contain carbon, but at much lower concentration. The most common organic sedimentary rock is **coal**. Coal is formed from the preservation and compaction of abundant plant material, buried in areas where oxygen is lacking (anoxic environments), such as swamps, wetlands, and bogs. All coal is combustible, and therefore can be ignited and burned; however, not all coal burns the same. In fact, there are grades of coal, which reflect increasing compaction or lithification.

Peat, typically dark brown (like potting soil), will contain obvious pieces of vegetation, and is typically the precursor to coal (**Figure 11.32**). In Ireland and Scotland there are peat bogs, from which the peat is mined, cut into bricks, dried, and used for the cooking and heating of homes.

Lignite coal is brittle with a low density (light **heft**) and has a matte brown or black color. It will also leave distinctive sooty marks on your fingers and hands. Typically, lignite coal contains 25%–35% carbon and has the lowest energy content of all coal ranks (**Figure 11.32**). Lignite coal deposits tend to be relatively young and were not subjected to extreme heat or pressure.

Lignite accounts for about 10% of total U.S. coal production, most from North Dakota and Texas.

Bituminous coal will also be brittle with a low density (light heft), but its black color has a bit more shine to it. Typically, bituminous coal contains 45%–86% carbon (**Figure 11.32**). Here in the United States, bituminous coal is the most abundant of the coal varieties and accounts for almost 50% of our coal usage. Significant deposits are located in Wyoming, West Virginia, Pennsylvania, Kentucky, and Indiana. Much of the bituminous coal worldwide is from the Carboniferous period of the late Paleozoic (about 300 million years ago). Much of the bituminous coal mined here in the US is used to generate electricity and for processing iron to make steel.

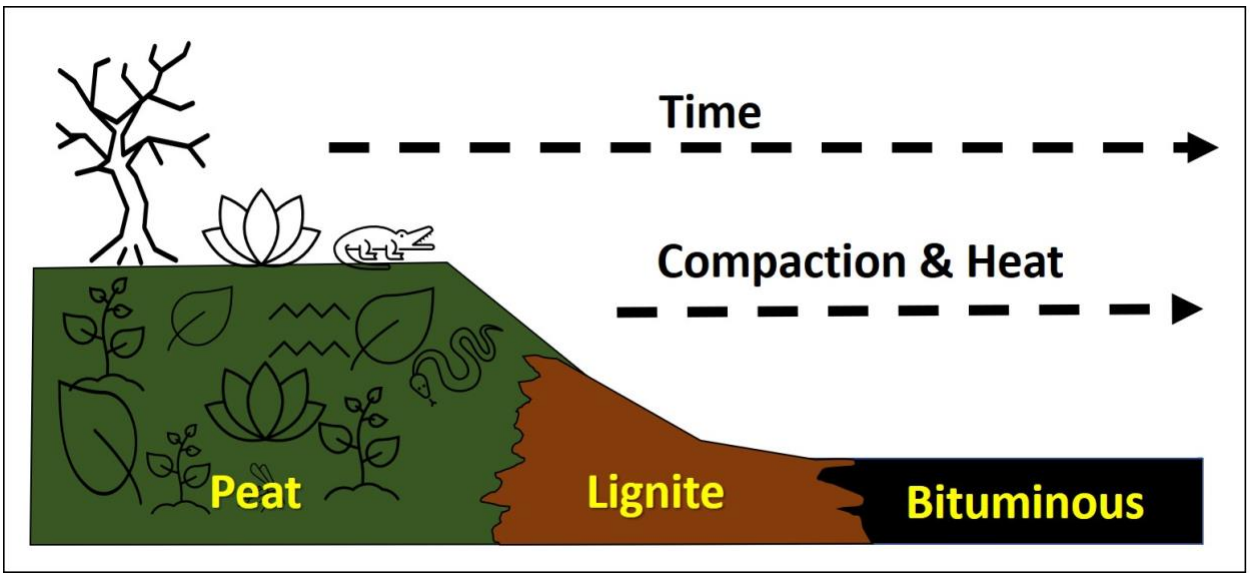

Figure 11.32: The stages of sedimentary coal formation.

Anthracite coal is much harder than the previously outlined coal varieties. It is black in color with a submetallic luster. Anthracite accounts for <1% of coal mined in the US, with most mined from northeastern Pennsylvania (the "Anthracite Belt"). Anthracite typically contains 86%–97% carbon and is the highest grade of coal. Technically, anthracite has undergone so much heat and pressure that it is considered a metamorphic rock. We will discuss this rock further in the metamorphic rock chapter.

Attributions

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- Figure 11.25: Derivative of “Oolitic Limestone” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte
- Figure 11.26: Derivative of “Chalk” (CC-BY 2.0; James St. John via Flickr) and “Emiliania huxleyi Coccolithophore” (CC-BY 2.5; Alison R. Taylor/University of North Carolina Wilmington Microscopy Facility via Wikimedia Commons) by Chloe Branciforte
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- Figure 11.29: “Fossiliferous Dolostone” (CC-BY 2.0; James St. John via Flickr)
- Figure 11.30: Derivative of “Chert Nodule” (CC-BY 2.0; James St. John via Flickr) and “Flint” (CC-BY 2.0; James St. John via Flickr) and “Radiolarian Heliodiscus umbonatus” (CC-BY 2.0; Picturepest via Flickr) and “Marine Diatoms” (CC-BY-SA 3.0; Mogana Das Murtey and Patchamuthu Ramasamy via Wikimedia Commons) by Chloe Branciforte
- Figure 11.31: “Salt Flats of Badwater Basin” (CC-BY 4.0; Chloe Branciforte, own work via Google Earth)
- Figure 11.32: “Stages of Coal Formation” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 11A: Concept Sketches and Sedimentary Processes

A **concept sketch** is a simplified drawing illustrating the main aspects of landscape or system. It is annotated with concise but complete labels that identify important features. Short sentences describe the processes that are occurring. The final aim is to show the relationships between features and processes. It is not simply a sketch labeled with only the names of features. See a rubric below for what is expected for each success level. Point values will be determined by your instructor.

Skill	Emerging	Progressing	Partial Mastery	Mastery
Identify **Features**	Incomplete labeling.	Some labeling.	Most clearly labeled.	Relevant features clearly labeled.
Identify **Processes**	Incomplete identification and description.	Incomplete identification or description.	Clear identification and description.	Relevant processes clearly identified and described.
Explain **the Connections and Relationships Between Features/Processes**	Incomplete connections/relationships.	Suggests some connections/relationship.	Most connections/relationships highlighted effectively.	Relevant connections/relationships highlighted effectively.
Demonstrate **Proper Use of Terminology**	Incomplete or inappropriate use of terminology/units. Frequent errors and misunderstanding of the subject.	Attempts use of appropriate terminology/units. Some errors and missing components.	Consistent use of appropriate terminology/units. Few errors or missing components.	Consistent and successful use of appropriate terminology/units.
Assess **Scientific Accuracy**	Lacks organization with frequent errors, demonstrating misunderstanding of the subject.	Drawings are readable, with occasional oversimplifications, errors and/or missing components.	Drawings are readable. Consistent use of symbology and/or colors/patterns to illustrate major features and/or processes.	Drawings are clearly readable with accurate details illustrated through appropriate symbols and/or colors/patterns. Sketch shows a scale.

Table 5.3: Rubric for geology concept sketches.

More on Concept Maps is available via NAGT/SERC, Teach the Earth.

1. Imagine a mountain composed of granite: *what does the resulting sediments' journey via a river to the ocean look like*? After reading the background information provided, draw a concept sketch for **"The Journey of a Pebble"**. Labels should be short sentences explaining the relationships between geologic features and processes.

The Journey of a Pebble

As the granite mountain is weathered, it is broken down into clasts of varying sizes. Larger, jagged clasts remain nearby and retain the composition of the original granite minerals (quartz, potassium feldspar, muscovite, Na-rich plagioclase feldspar). Clasts that continue their journey, perhaps by a fast-moving river, are changed. During transportation, clasts collide with one another becoming progressively smaller and more rounded. As the topography flattens, the river's velocity begins to slow, triggering deposition of larger clasts, while smaller clasts continue to be transported. As the river meets the beach and ocean, velocity will continue to slow down, depositing smaller and smaller sediments, until nothing is left. Throughout this journey, clasts will also undergo chemical weathering, fundamentally altering the original mineralogy of the granite. Feldspars and micas are transformed into clay-minerals, like kaolinite or montmorillonite, and the iron-bearing minerals alter to hematite. The only mineral that does not chemically change is quartz.

Attributions

- Table 5.3: “Concept Sketch Rubric” (CC-BY 4.0; Chloe Branciforte and Emily Haddad, own work)

Activity 11B: Identifying Sedimentary Rocks

For this section, you will need the following materials before you begin:

- Sedimentary rock samples (or kit) selected by your instructor,
- Glass plate, streak plate, and a hand lens (or magnifying glass)
- Bottle of diluted HCl (optional)

1. Using the kit provided, begin by separating the rocks into two piles, a clastic and a non-clastic pile. ***Remember, sedimentary rocks must be categorized as either clastic OR non-clastic; a sample cannot be both.*** For each sample number, indicate whether the sample is clastic or non-clastic by placing an X in the appropriate column below.

Table 11.6: Table to complete for Question 1 of Part A.

Sample Number	Place an X below for **Clastic**	Place an X below for **Non-clastic**

Using the same samples, and your Answers from questions 1 & 2, fill out **Table 11.7** below.

2. *If the sample is clastic,* determine the **grain size**, **shape,** and overall **sorting**.

3. *If the sample is non-clastic*, indicate whether the sample is **organic (O)** or **chemical/biochemical (C/BC)**. Then determine the **dominant composition** of the rock.

4. Using the characteristics of each rock, identify each sample by name. Add the rock name to the final column of the table below.

Table 11.7: Table to complete for Question 2-4 of Part A.

Sample Number	***If the sample is clastic*:**			***If the sample is non-clastic*:**		**Sedimentary Rock Name**
	Grain size	*Grain shape*	*Sorting*	*organic (O) or chemical/biochemical (C/BC)*	*Dominant composition*	

5. Chert and limestone are both fine-grained sedimentary rocks. What are two tests you can use to tell them apart?

6. What characteristic distinguishes sedimentary breccia from conglomerate?

7. How can sorting, rounding, and grain size be useful for understanding depositional environments? Use examples in your explanation.

Attributions

- Table 11.6: “Clastic vs. Non-clastic” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 11.7: “Name That Sedimentary Rock” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 11C: Identifying Depositional Environments

Use the browser version of Google Earth to explore depositional environments. For each locality, think about the types of sediments that are accumulating, the types of weathering that would occur, as well as the presence of any sedimentary structures.

1. Search for 39°05'52.5"N 84°30'56.2"E and zoom out to an eye altitude (camera) of 15 miles. The large-scale structures in this sedimentary environment are asymmetrical ripples (at this scale and size they are known as dunes). Zoom in and out and examine the sedimentary environment. What type of sedimentary environment is this?

2. What type of weathering do you think is most prominent in this sedimentary environment?

    a. Mechanical weathering from a current
    b. Dissolution
    c. Frost Wedging
    d. Hydrolysis

3. Study the large dunes in this image (zoom out to an eye altitude of ~400 miles). These structures can indicate the direction that the wind is blowing. What is the predominant wind direction in this area? (Hint: toggle between 2D and 3D to get a better perspective).

    a. north to south
    b. south to north
    c. east to west
    d. west to east

4. Search for 64°01'03.6"N 16°52'56.6"W and zoom out to an eye altitude (camera) of ~25,000 ft. What type of sedimentary environment is this?

5. Which type of weathering do you think is most prominent in this sedimentary environment?

    a. Physical weathering
    b. Chemical weathering

6. Provide a specific example of the weathering you type you selected.

7. Describe the likely appearance (rounding, sorting, size) of the sediment here?

8. When the sediment you see today lithifies, what type of sedimentary rock would you expect to be most abundant in this area?

9. Search for 36°07'31.4"N 116°45'34.7"W and zoom out to an eye altitude (Camera) of 23,000 ft. What type of sedimentary environment is this?

10. What type of sediment would you expect to find in this depositional environment?

- **a.** Mostly mature clastic sediments with some biochemical and chemical sedimentary sediments
- **b.** Mostly biochemical and chemical sedimentary sediments with some mature clastic sediments
- **c.** Exclusively organic sediments
- **d.** Exclusively biochemical sediments
- **e.** Exclusively immature clastic sediments

11. Search for 44°42'17.0"N 1°05'23.9"W and zoom out to an eye altitude (Camera) of ~17 miles. Notice the depth of this shallow bay (Arcachon Bay, France). This bay dries out at times and later greatly expands in size daily. What sedimentary structure(s) would you likely find in this area because of this?

12. What type of sedimentary environment is this?

13. What type of trace fossils would you expect to find at this location?

14. Search for 36°40'51.6"N 117°33'22.5"W and zoom out to an eye altitude (Camera) of ~33,000 ft. What type of sedimentary environment is this?

15. Which type(s) of sedimentary rocks and minerals would likely form here?

16. Search for 20°20'23.9"S 150°38'29.1"E. Zoom out far enough to notice where you are in the world, then zoom back in to an eye altitude (Camera) of ~20 miles. What type of sedimentary environment is this?

17. Think about the origin of this marine formation and consider the latitude to assess climatic conditions. What is the most abundant type of rock you would expect to form in this sedimentary environment?

18. If the sea level dropped 1,000 feet and this sedimentary environment stopped being built and began to break down, what type of weathering would be most likely to occur on these rocks?

- **a.** Fracturing from the addition or subtraction of pressure
- **b.** Dissolution
- **c.** Frost Wedging
- **d.** Hydrolysis

19. Search for 31°00'43.6"N 81°25'40.9"W and zoom out to an eye altitude (Camera) of 1,500 ft. What type of sedimentary environment is this?

20. What type of sediment would you expect to find in this depositional environment?

- **a.** Mostly mature clastic sediments with some biochemical and chemical sedimentary sediments
- **b.** Mostly biochemical and chemical sedimentary sediments with some mature clastic sediments
- **c.** Exclusively organic sediments
- **d.** Exclusively biochemical sediments
- **e.** Exclusively immature clastic sediments

21. Search for 36°53'02.3"N 122°01'12.1"W and zoom to an eye altitude (Camera) of 33 mi. Make sure you can still see Moss Landing in your frame. What landform is located here?

22. Consider the placement of this landform. Which depositional environment is represented here?

23. Which geologic process likely formed this landform?

Chapter 12: Groundwater Processes

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Understand the distribution and flow of groundwater, including the placement of the water table.
- ✔ Learn the main features and hazards associated with karst topography.

Thumbnail for Chapter 12:

Thumbnail: "Pumpkin Palace in Hurricane Crawl Cave" (Public Domain; NPS)

The Water Cycle

How many times a day do you take water for granted? Do you assume the tap will be flowing when you turn on your faucet? That the shower will turn on, the toilet will flush, and you'll have water to cook your meals? Not only is water necessary for many of life's functions, it is also a considerable geologic agent. Water can sculpt the landscape dramatically over time, by both carving canyons and depositing thick layers of sediment. Some of these processes are slow and result in landscapes worn down over time; others, such as floods, can be dramatically fast and dangerous.

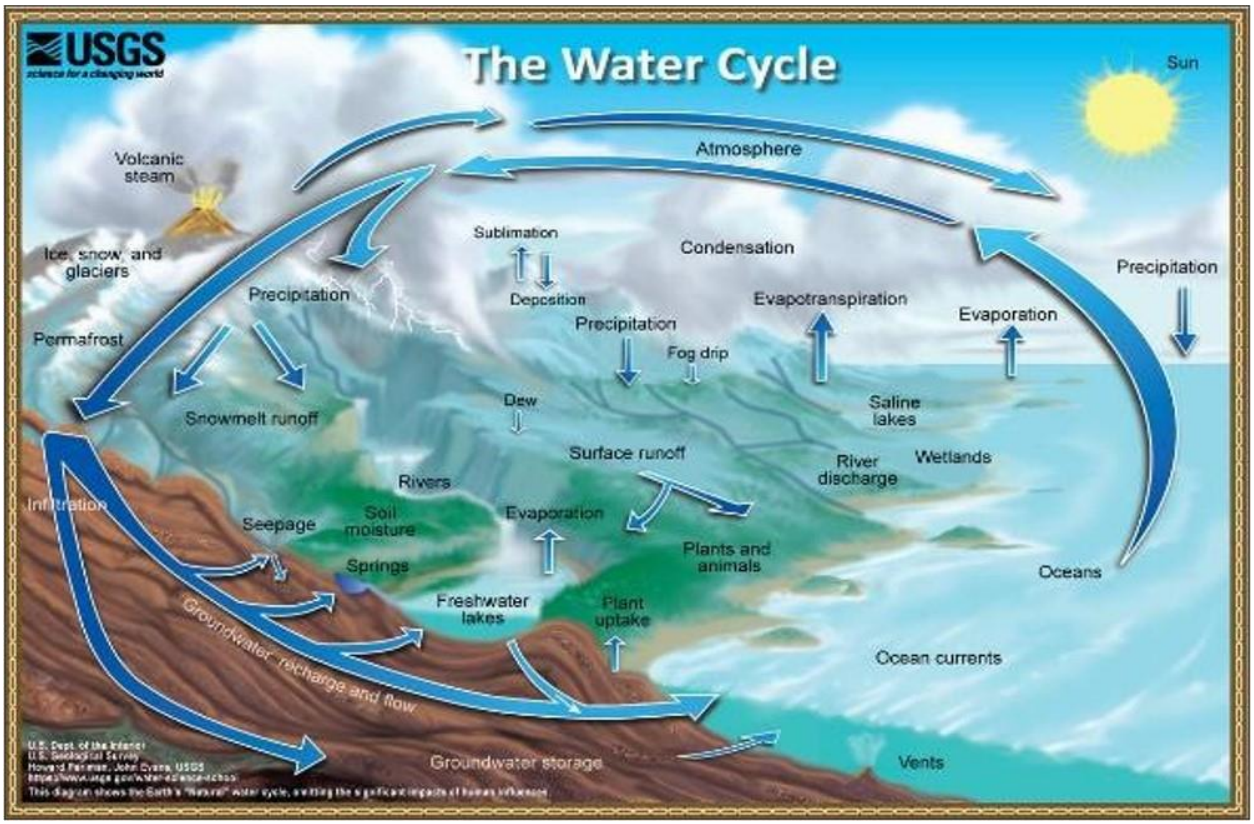


Figure 12.1: Earth's water is always in movement, and the natural water cycle (hydrologic cycle), describes the continuous movement of water on, above, and below the surface of the Earth. Water is always changing states between liquid, vapor, and ice, with these processes happening in the blink of an eye and over millions of years.

What happens to water during a rainstorm? Imagine that you are outside in a parking lot with grassy areas nearby. Where does the water from the parking lot go? Much of it will run off as sheet flow and eventually join a stream. What happens to the rain in the grassy area? Much of it will infiltrate, or soak into the ground. Water is continually recycled through the atmosphere, to the land, and back to the oceans. This movement of water through the Earth System is

referred to as the **hydrologic (water) cycle** (**Figure 12.1**). At Earth's surface, this cycle, powered by the sun, operates easily since water can change form from liquid to gas (or water vapor) quickly. The majority of water is called surface water and is stored in oceans, but there are freshwater resources in lakes, rivers, and trapped away in glaciers and ice sheets (discussed in a future chapter; **Figure 12.2**). Additional water resources are also found in the ground, and that's what we'll be discussing here.

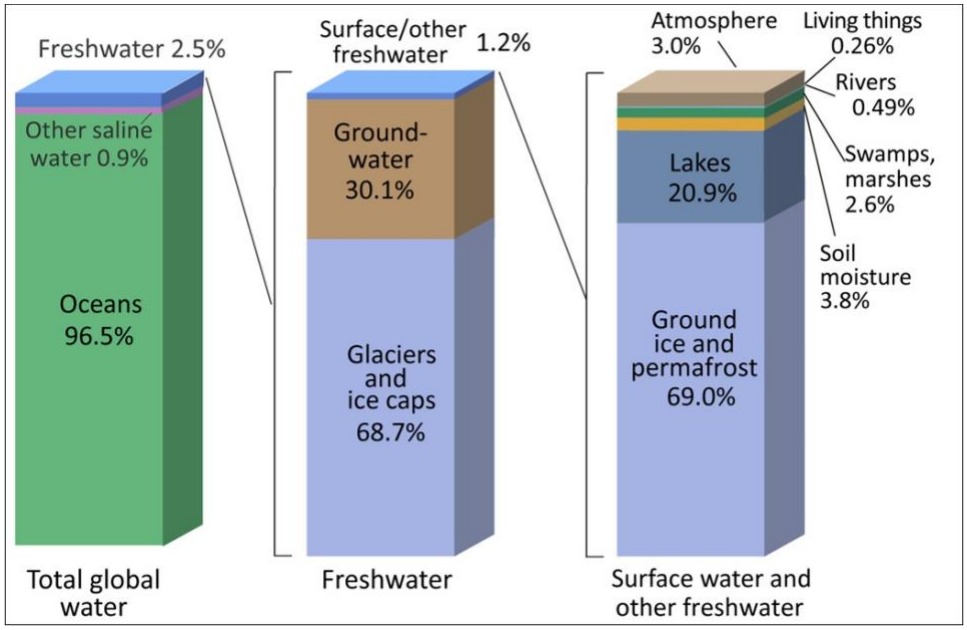


Figure 12.2: Most of the Earth's water is found in oceans and is therefore saltwater. Earth's freshwater sources are mostly locked within glaciers and ice caps and as groundwater. Rivers and lakes make up only a small fraction of Earth's freshwater resources.

Those who study water, water resources, or the landforms made by water, may have many titles, including hydrologist, hydro-geologist, geomorphologist, or geochemist, to name a few. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including in mining and natural resource extraction or in hazard mitigation and assessment. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have

wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 12.1: “The Water Cycle” (Public Domain; Howard Perlman and John Evans, USGS)
- Figure 12.2: “Where is Earth’s Water?” (Public Domain; USGS Water Science School

What Is Groundwater?

What do you picture when you hear the word "groundwater"? Flowing rivers underground? Hidden lakes in dark caves? The vast majority of groundwater is actually held in porous rock or sediment, and is slowly seeping from one small pore to another, much like how water is absorbed into a sponge (**Figure 12.3**).

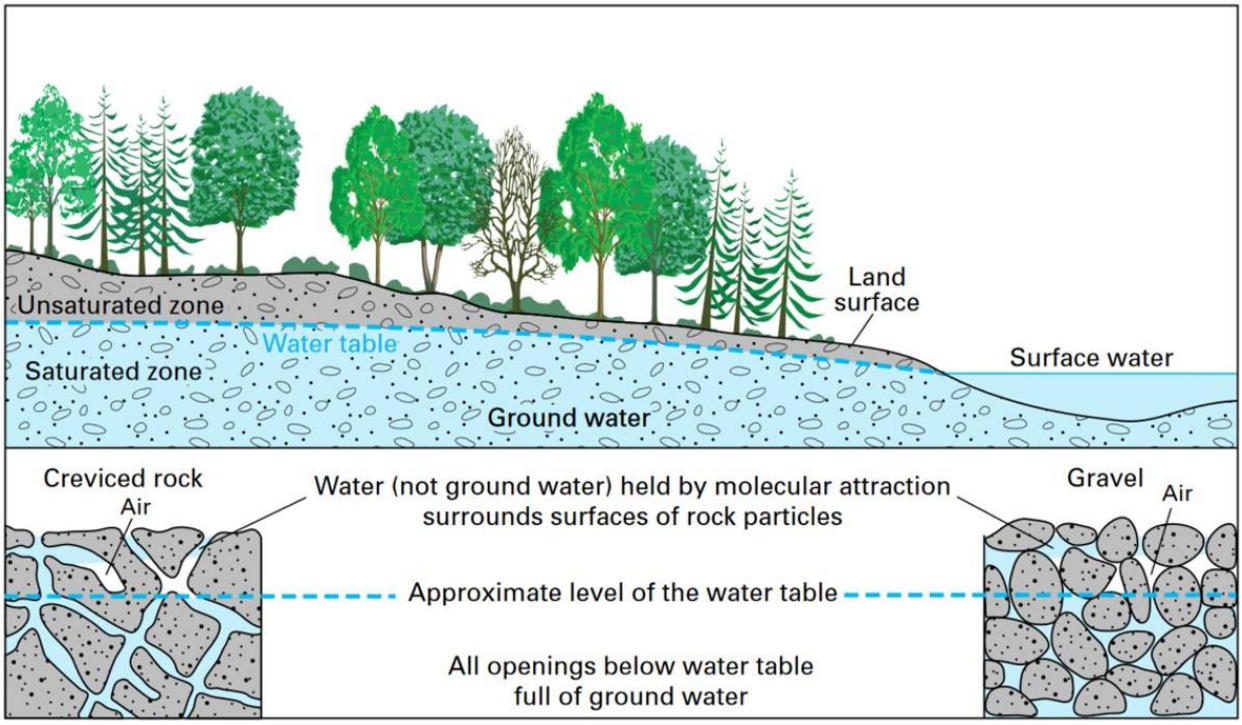


Figure 12.3: Groundwater is simply the subsurface water that fully saturates pores or cracks in soils and rocks. Between the land surface and the aquifer water is a zone that hydrologists call the unsaturated zone.

Have you ever been to the beach and dug a hole, only to have it fill with water from the base? If so, you had reached the **water table**: the boundary between the unsaturated and saturated zones. Rocks and soil at and just beneath the land's surface are part of the **unsaturated zone**; pore spaces here are filled with air. Moving down from the surface, we will sooner or later reach the water table, where rocks and soil pore spaces are filled with water in the **saturated zone**. The saturated zone beneath the water table is called an **aquifer**, which are potentially huge storehouses of water.

The water table is said to mimic topography, in that it generally lies near the surface of the ground (often tens of feet below the surface, though this can vary greatly with location) and rises with hills and sinks with valleys, often discharging into streams. The water table receives

additional inputs when rainfall infiltrates into the ground; this is called **recharge**. The position of the water table is dynamic: during droughts it will lower, and during wet times it will rise.

Two important properties of groundwater that influence its availability and movement are porosity and permeability. **Porosity** refers to the open or void space within the rock (**Figure 12.4**). It is expressed as a percentage of the volume of open space compared to the total rock volume. Porosity will vary with rock type. Many rocks with tight interlocking crystals (such as igneous and metamorphic rocks) will have low porosity since they lack open space. Sedimentary rocks composed of well-sorted sediment tend to have high porosity because of the abundant spaces between the grains that make them up. Envision a room filled from floor to ceiling with basketballs (similar to a rock composed completely of sand grains). Now add water to the room. The room will be able to hold a good deal of water, since the basketballs do not pack tightly due to their shape. That would be an example of high porosity.

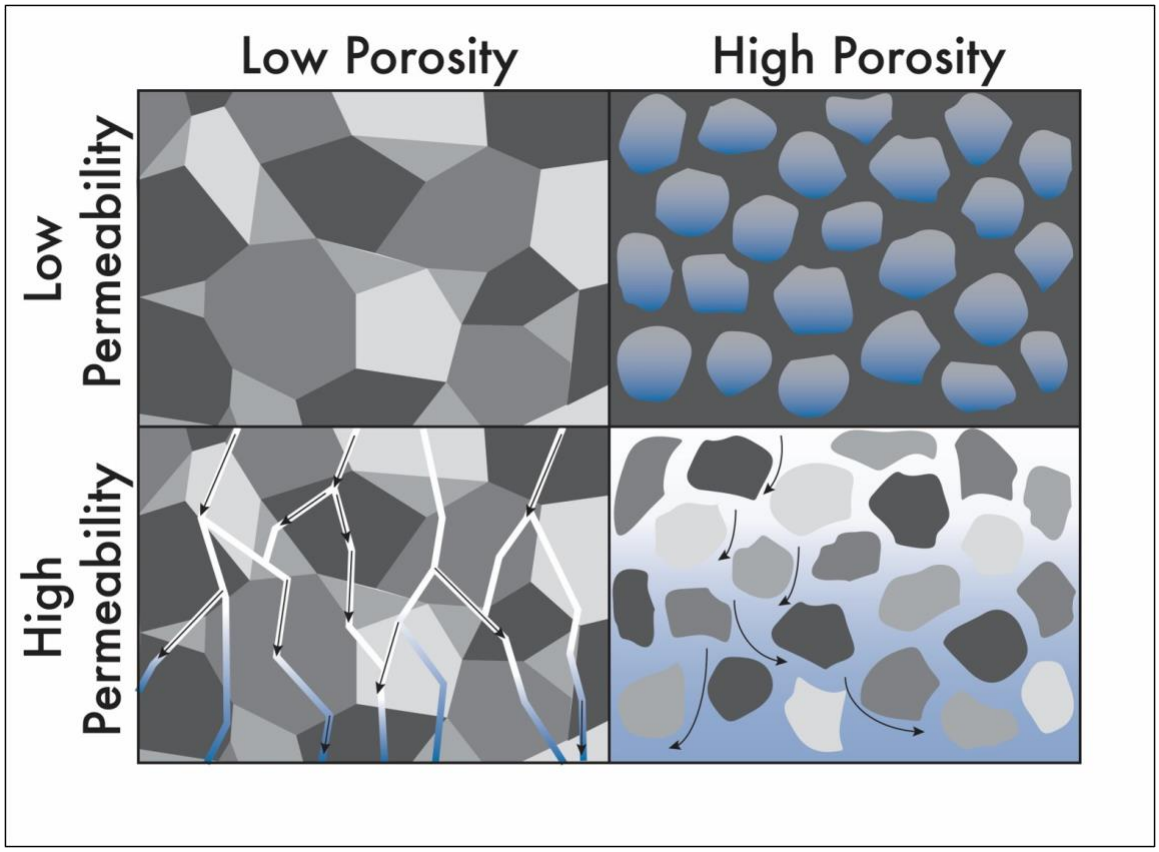


Figure 12.4: Groundwater is simply the subsurface water that fully saturates pores or cracks in soils and rocks. Between the land surface and the aquifer water is a zone that hydrologists call the unsaturated zone.

If the open spaces are connected, water will be able to flow through them; this is why rocks that are **permeable** make good aquifers (**Figure 12.4**). Sedimentary rocks, such as sandstone

and limestone, are good aquifers. Rocks that are impermeable make confining layers (aquicludes or aquitards) and prevent the flow of water. Examples of confining layers would be sedimentary rocks like shale (composed of tiny clay and silt grains) or unfractured igneous or metamorphic rock. In a **confined aquifer**, the aquifer is topped by a confining layer (**Figure 12.5**). In an **unconfined aquifer**, the top of the aquifer is the water table.

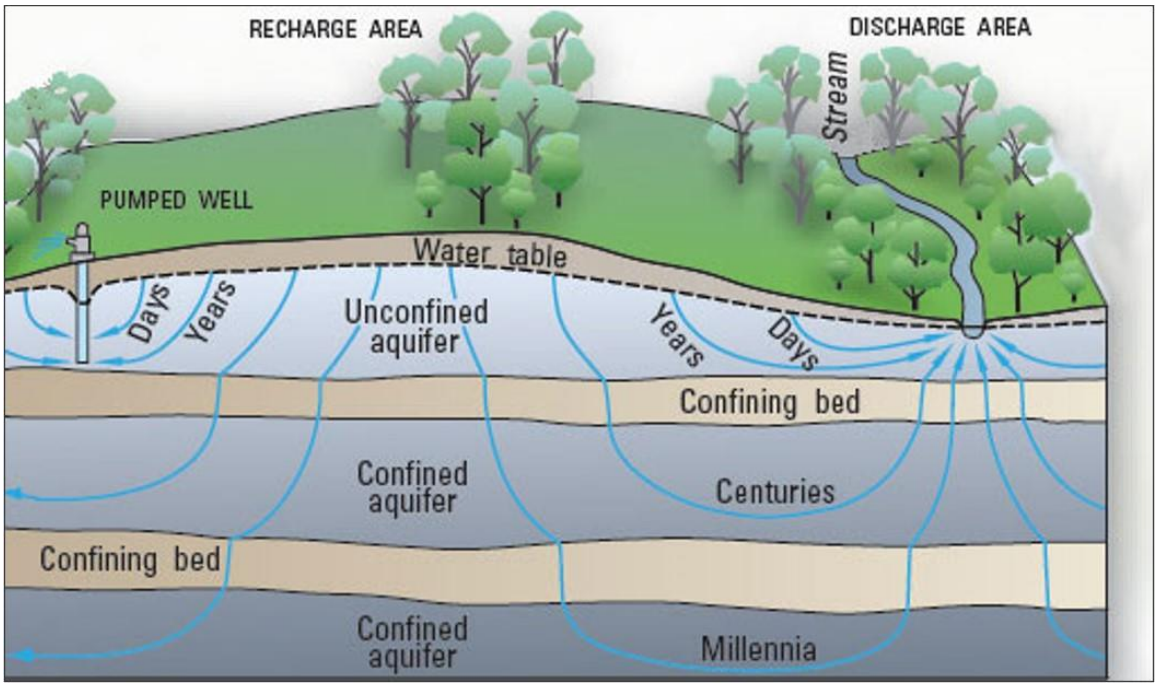


Figure 12.5: Groundwater flows underground at different rates. The direction and speed of groundwater movement is determined by the various characteristics of aquifers and confining layers of subsurface rocks in the ground. Water moving below ground depends on the permeability and on the porosity of the subsurface rock. If the rock has characteristics that allow water to move relatively freely through it, then groundwater can move significant distances in several days. But groundwater can also sink into deep aquifers where it takes thousands of years to move back into the environment, or even go into deep groundwater storage, where it might stay for much longer periods.

Just like surface runoff, groundwater generally flows from areas of higher elevation to lower elevation in the shallow subsurface. Approximately 20% of the water used in the United States is groundwater, and this water has the potential to become contaminated, mostly from sewage, landfills, industry, and agriculture. The movement of groundwater helps spread the pollutants, making containment and mitigation a challenge.

Attributions

- Figure 12.3: “Groundwater is the Saturated Zone of Soil/Rock Below the Land Surface” (Public Domain; USGS)
- Figure 12.4: “Porosity and Permeability” (CC-BY 4.0; Emily Haddad, own work)
- Figure 12.5: “Conceptual Groundwater-Flow Diagram” (Public Domain; USGS)

Karst Topography

The sedimentary rock limestone is composed of the mineral calcite, which is water soluble; this means it will dissolve in water that is weakly acidic. In humid areas where limestone is present, water dissolves away the rock, forming large cavities and depressions that vary in size and shape. As more dissolution occurs, the caves become unstable and collapse, creating **sinkholes** (**Figure 12.6**).

Figure 12.6: *Top right:* The Winter Park sinkhole of Central Florida. *Bottom left:* Every circular feature in this aerial photo is a sinkhole filled with water.

These broad, crater-like depressions are typical of karst topography, named after the Karst region in Slovenia. **Karst topography** is characterized by sinkholes, sink lakes (sinkholes filled with water), caves, and disappearing streams (surface streams that disappear into a sinkhole) (**Figure 12.7**).

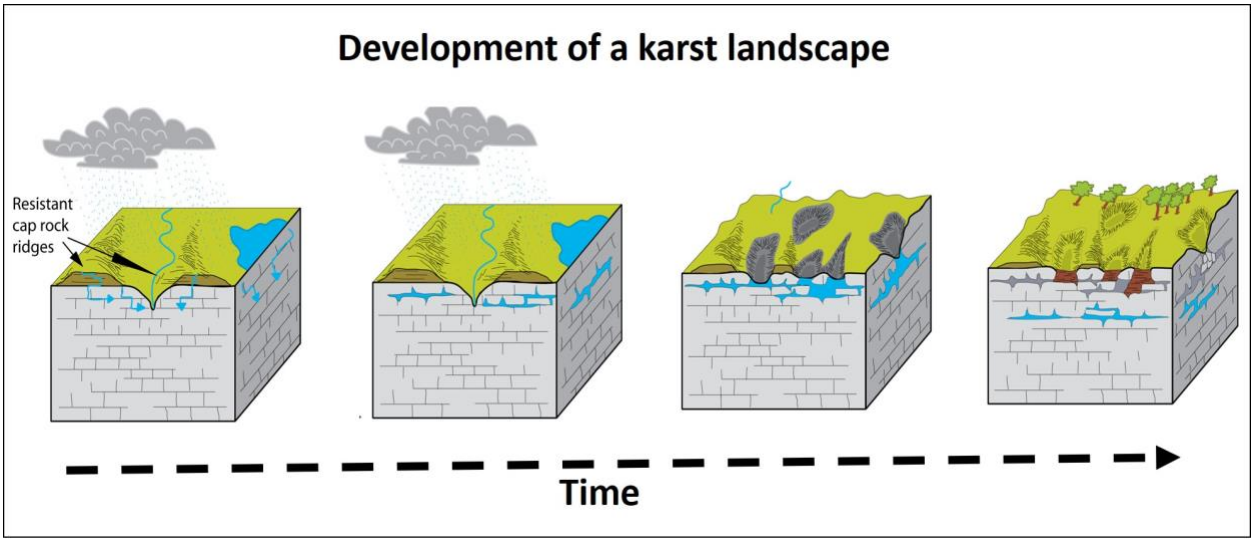


Figure 12.7: Series of generalized cross-sectional views of the development of a karst landscape.

Living on a karst landscape poses unique challenges, and approximately one fourth of Americans in the lower 48 states live in these regions (**Figure 12.8**).

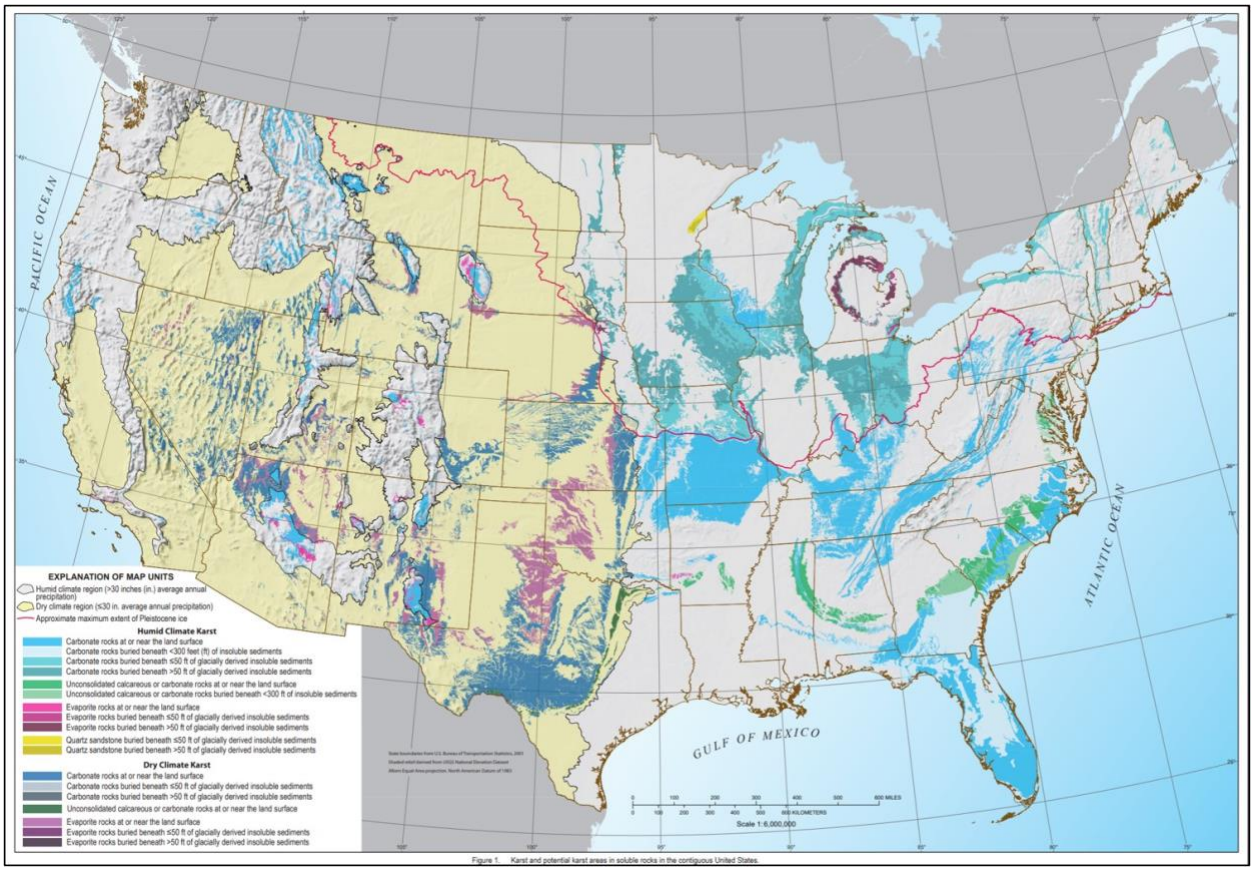


Figure 12.8: Karst and potential karst areas in soluble rocks in the contiguous United States.

Attributions

- Figure 12.6: Derivative of “Winter Park Florida Sinkhole of 1981” (Public Domain; USGS) by Chloe Branciforte
- Figure 12.7: Derivative of “Development of Karst Landscapes” (Public Domain; Trista L. Thornberry-Ehrlich, Colorado State University via NPS) by Chloe Branciforte
- Figure 12.8: “Karst Areas of the Contiguous United States” (Public Domain; USGS)

Activity 12A: Groundwater Flow

Many gas stations use underground storage tanks (UST) to store fuel below the ground. You have likely seen a tanker truck at a gas station filling up an UST. These UST's can leak, and, as a result, gasoline can percolate down to the water table. On **Figure 12.9** below, a business using a well has detected gasoline in their groundwater. There are several gas stations in the diagram, and each has the potential to have a leaking UST. Seven monitoring wells are installed in the area; you are provided the data about the water table elevation within each well (**Table 12.1**). To detect the source of the potential leak, you will need to determine its flow path.

Figure 12.9: Groundwater map to use in Activity 12A: Groundwater Flow.

Monitoring Well	Water Table Elevation (feet)
1	794
2	790
3	788
4	786
5	786
6	783
7	780

Table 12.1: Water table elevations for the monitoring wells located on Figure 12.9.

1. Draw (either in pencil or digitally) contour lines for the water table (WT) elevation. Use an interval of 2 feet. Add WT elevations to each of the wells on the map.

2. Determine the direction of groundwater flow. Draw arrows to illustrate the direction.

3. Indicate, with a star, the gas station most likely to be the source of the leak.

4. Which gas station is the most likely source of the gasoline leak?
   a. Station A
   b. Station B
   c. Station C

5. How do you know?

6. Is the school likely to be at risk of contamination from this same leak?
   a. Yes
   b. No

7. How do you know?

8. Is the church likely to be at risk of contamination from this same leak?
   a. Yes
   b. No

9. How do you know?

Attributions

- Figure 12.9: “Groundwater Map” (CC-BY 4.0; Emily Haddad, own work)
- Table 12.1: “Groundwater Monitoring” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 12B: Caves and Karst in California

1. Download the Google Earth KML file for the Geology of California. In the browser version of Google Earth, click on "Projects" along the toolbar. Select "New Projects" and "import KML file from computer". Select the file you just downloaded: "cageol". This file should now show in the browser version of Google Earth.

2. Now search for Moaning Caverns. Zoom in to Moaning Caverns Adventure Park.

3. Click on the color beneath the location pin. What type of rock is this?

4. What is the probable geologic age of this rock?

5. Click on "Detailed description". This will bring up additional information about the geologic unit. Under "Stratigraphic unit" there are a number of named formations and groups. What is the probable name of this rock formation?

6. Now search for Black Chasm Cave.

7. Click on the color beneath the location pin. What type of rock is this?

8. What is the probable geologic age of this rock?

9. Click on "Detailed description". This will bring up additional information about the geologic unit. Under "Stratigraphic unit" there are a number of named formations and groups. What is the probable name of this rock formation?

Activity 12C: Karst Topography and Topographic Maps

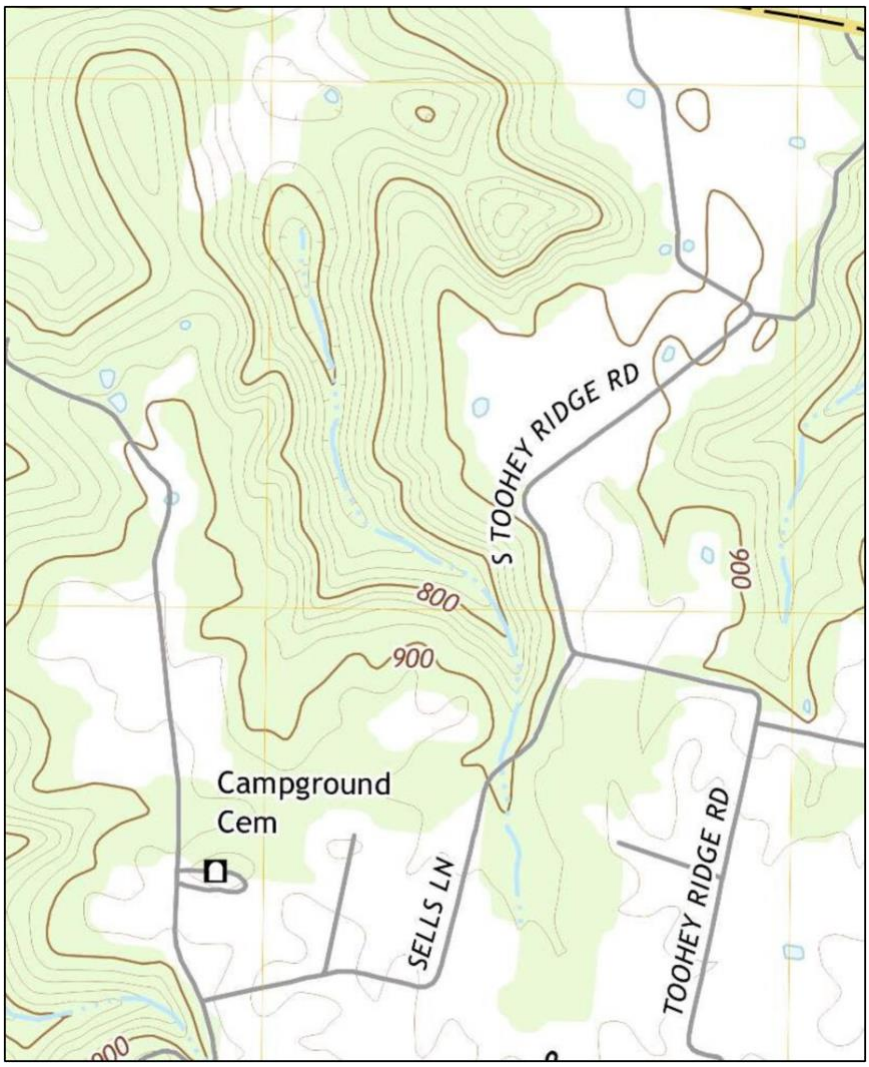


Figure 12.10: Topographic map to use in questions 1 & 2 of Activity 12C.

1. Locate the unnamed river to the northwest of S Toohey Ridge Road. In which direction does this river flow?

   a. How can you tell?

2. Follow the creek along its path. Where does it wind up?

   a. How can you tell?

3. Using the browser version of Google Earth, search for 28 38 01.92N 81 22 44.78W and zoom out to an eye altitude of 13,000 ft. How were these lakes likely formed?
    a. they were human-made – all are dammed
    b. they are formed by large rivers in the area
    c. as sinkholes, as underlying soluble rock was dissolved and areas collapsed
    d. they are impact structures that filled with water

4. What type of bedrock is likely present in this area?

    a. How can you tell?

Attributions

- Figure 12.10: “Mammoth Cave Quadrangle” (CC-BY 4.0; Chloe Branciforte via USGS TopoView)

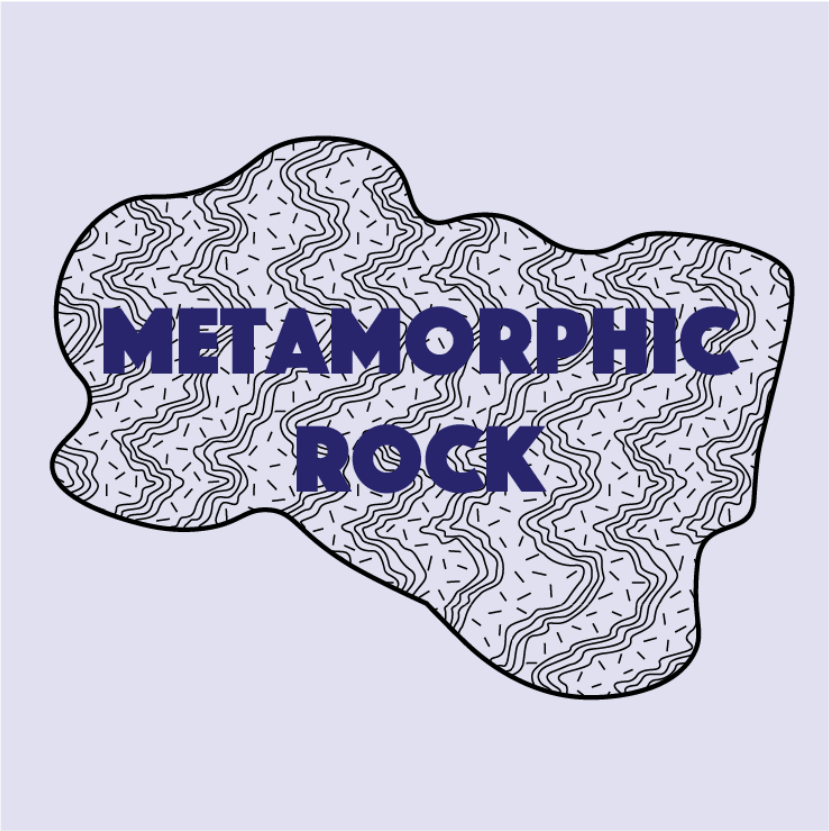
Chapter 13: Metamorphic Rocks & Processes

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Classify metamorphic rocks based on their texture and mineral content and explain the origins of these differences.
- ✔ Determine the grade of metamorphism based on grain size and possible index minerals.
- ✔ Recognize metamorphic environments and types of metamorphism.

Thumbnail for Chapter 13:



Thumbnail: "Metamorphic Rock" (CC-BY 4.0; Emily Haddad, own work)

What Is the Rock Cycle?

The rock cycle is a circular diagram that demonstrates the process by which rocks are continually recycled throughout geologic time. All rocks can be classified into one of three groups: igneous, sedimentary, or metamorphic. This rock classification is based on the origin of each of these rock types, or the processes that form the rock. The Rock Cycle (Figure 13.1), represents the processes that produce each of the rock types. In Chapter 7, we explored igneous rocks, which are produced through the melting of rock and eventual cooling of lava or magma; as cooling occurs, crystals may form. In Chapter 11, we investigated sedimentary rocks, which are produced via the processes of weathering (the chemical and physical breakdown of material at Earth's surface that produces sediments), erosion (the movement and deposition of sediments), and lithification (the compaction and cementation of sediments). We've now reached metamorphic rocks, which are produced via the agents of change, primarily heat and pressure that typically result in the recrystallization of minerals.

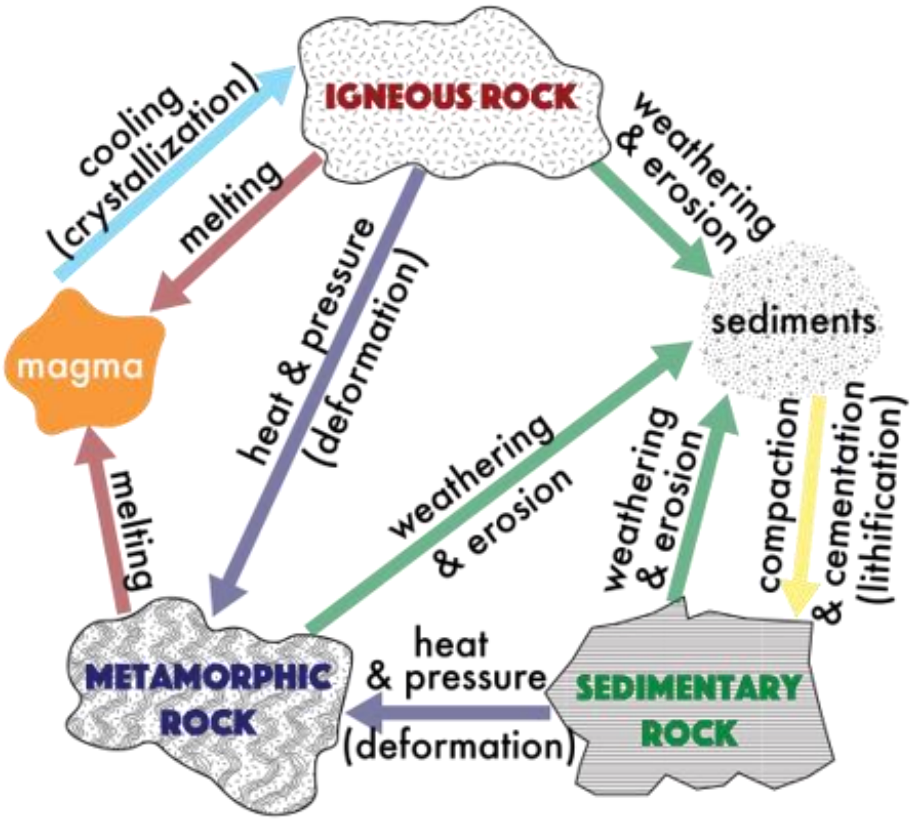


Figure 13.1: The processes of the rock cycle.

Attributions

- Figure 13.1: “The Rock Cycle” (CC-BY 4.0; Emily Haddad, own work)

What Is a Metamorphic Rock?

The word **metamorphism** means to change form; for rocks, this means a recrystallization of minerals (crystals) under subsolidus conditions (temperatures too low for melt production). All rocks form at certain temperatures and pressures at, or more commonly, beneath the Earth's surface. These rocks are most stable at the conditions under which they form. Therefore, changing the temperature and/or pressure conditions may lead to a different rock, one that changed in order to be stable under the new external conditions. This new rock that forms in response to changes in its physical and chemical environment is called a metamorphic rock. A metamorphic change can also occur if the rock's composition is altered by hot, chemically reactive fluids, causing a change in the mineral content of the rock.

Metamorphic rocks form by the physical and sometimes chemical alteration of a pre-existing rock. To distinguish between the pre-existing rock and the new metamorphic one, the term **protolith** (*proto-* meaning "original" and *-lith* meaning "rock"), or parent rock, is used to describe the pre-existing rock (**Figure 13.2**). All metamorphic rocks have at least one protolith that was altered during metamorphism. Igneous, sedimentary, or in some cases, even metamorphic rocks can be altered into a completely new or different metamorphic rock.

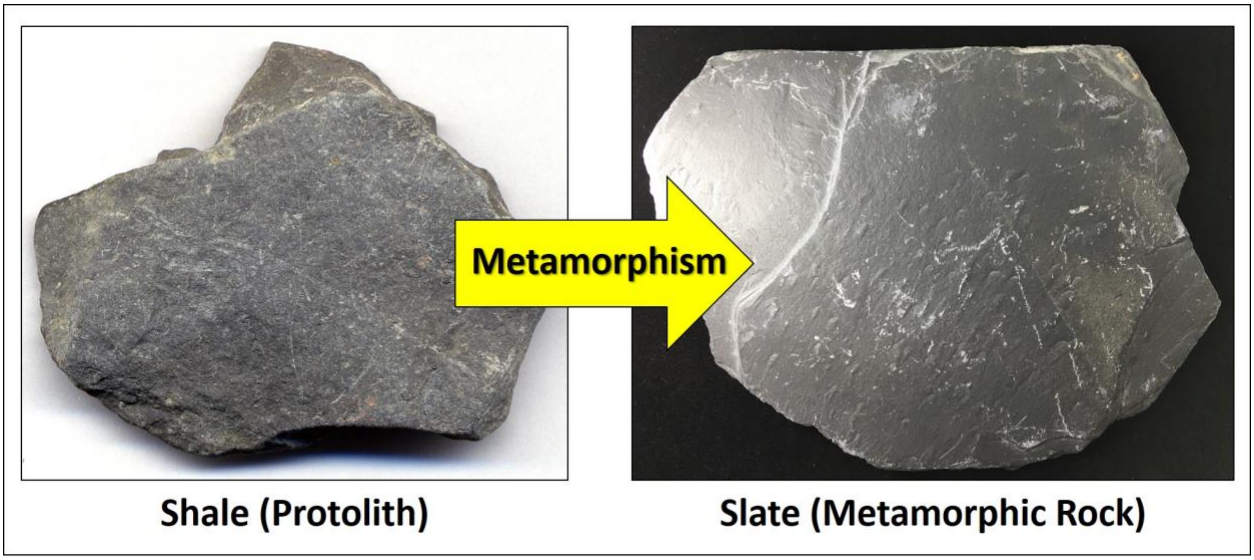


Figure 13.2: Heat and pressure alter shale, the protolith, to slate.

A person who studies metamorphic rocks is typically referred to as a metamorphic petrologist. A petrologist is a geoscientist that studies rocks and the conditions under which rocks form. A metamorphic petrologist specializes in metamorphic rocks and their unique conditions of formation. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where

they teach and/or do research, and at state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including mining and natural resource extraction. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 13.2: Derivative “Gray Shale” (CC-BY 2.0; James St. John via Flickr) and “Slate” (CC-BY 4.0; Chloe Branciforte, own work) by Chloe Branciforte

Agents of Metamorphism

Pressure

All rocks beneath the surface of the earth experience an increase in pressure due to the weight of the overlying sediment and rock layers. Therefore, with increasing depth there is a corresponding increase in pressure. Typically, this **lithostatic (confining) pressure** is equal in all directions and will not necessarily cause a rock to become metamorphic (**Figure 13.3A**). Have you ever dived deep into a pool, lake, or ocean? As you descend, your eardrums experience hydrostatic pressure; this is similar to what sediments and rocks experience under lithostatic pressure. Lithostatic pressure may alter the overall rock or sediment volume but will not cause a change in overall shape. For example, lithostatic pressure can cause clasts to become more closely packed or reduce pore space within a clastic sedimentary rock.

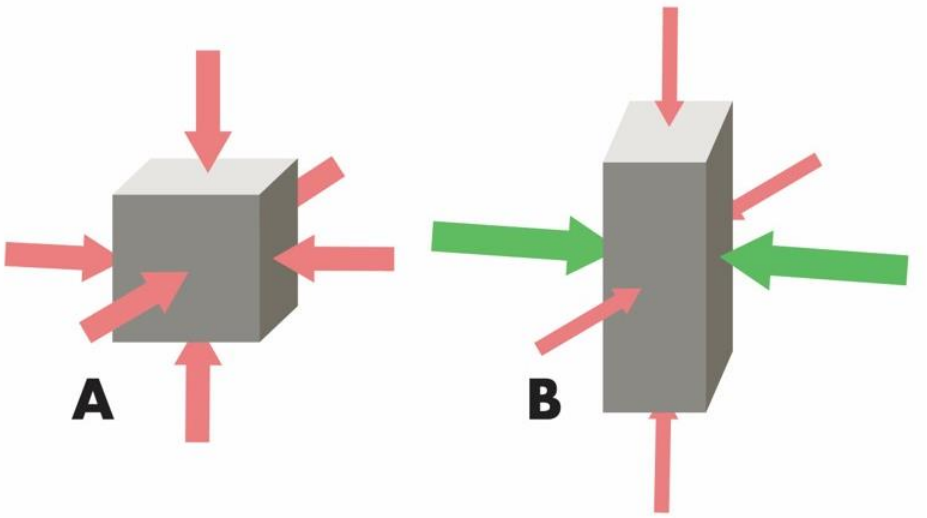


Figure 13.3: Confining pressure (left) and differential pressure (right).

What happens if the pressure on a rock is unequal, and the rocks become squeezed in one direction more than another direction? This is known as **differential (directional) pressure**, and can result in a significant change in the appearance of a rock (**Figure 13.3B**). Imagine deformation happening to all the grains in the sedimentary rock or to all the crystals in an igneous rock. The resulting rock will have minerals aligned in a certain direction, through bond breaking and **recrystallization**. The result is a rock with a metamorphic pattern called a foliation. **Metamorphic foliations** are the patterns seen in a rock that has experienced differential pressure. Foliations may be flat or have a wavy appearance possibly due to more than one direction of greatest pressure (**Figure 13.4**). Some rocks may also develop what is

called a **lineation**, which can be formed by an elongation of minerals that form a linear feature through the rock.

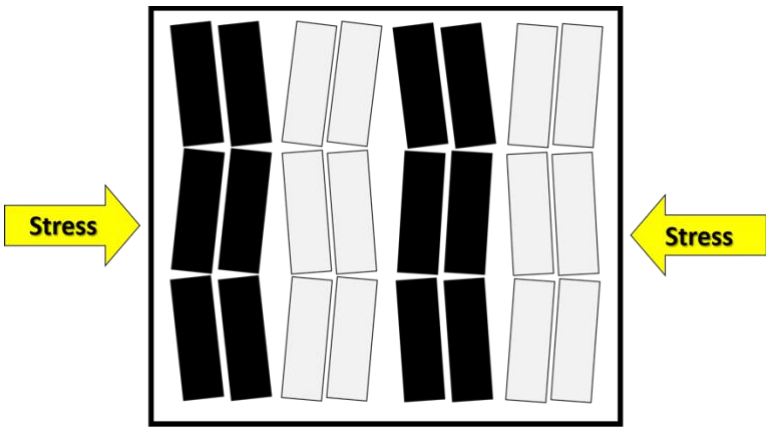


Figure 13.4: Foliation formed by the realignment of micas and clays under differential stresses.

Temperature

Metamorphism often involves both an increase in temperature and pressure changes; however, the broad classification for metamorphism into low-, medium-, and high-grades of metamorphic change exists mainly due to temperature conditions. Higher temperatures increase the vibrational energy between the bonds linking atoms in the mineral structure, making it easier for bonds to be broken and minerals to recrystallize into new crystal shapes; high temperatures can also sometimes result in the development of foliation and lineation outlined above, even without differential pressure conditions. When temperatures are increased, there can be a corresponding increase in mineral sizes as initially small minerals become fused into larger crystals. This fusing of numerous smaller mineral sizes into fewer, yet larger, is also an

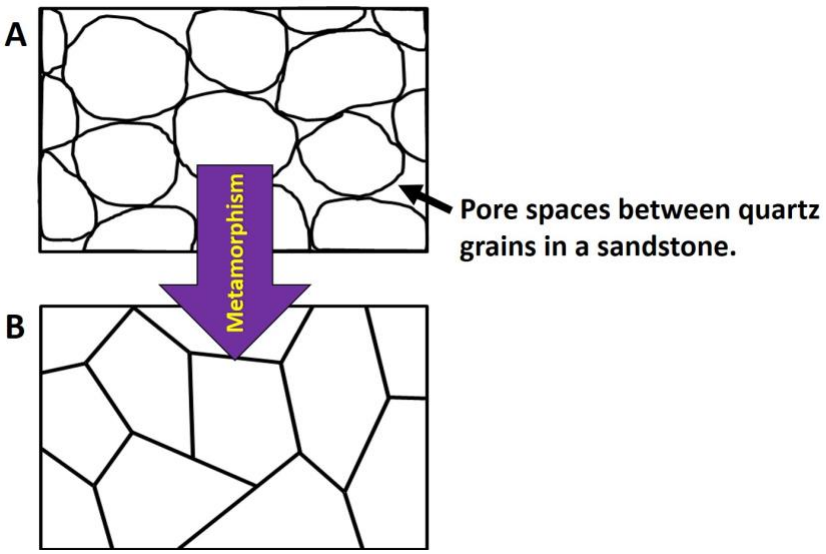


Figure 13.5: An example of the recrystallization of crystals into larger sizes due to increased temperature: A) a sedimentary rock with rounded quartz grains, and pore spaces between the grains. B) a metamorphic rock with larger, interlocking quartz crystals due to increased temperature conditions.

example of recrystallization (**Figure 13.5**).

Why do increasing temperatures lead to increased grain sizes? In general, a mineral grain or crystal is most stable when it has a low surface area to volume ratio, therefore large grains are more stable than small grains. Increasing the grain size results in a greater increase in volume as opposed to a smaller increase in the surface area. Why does stability matter? Rocks become unstable when their environment changes, and through a recrystallization process (metamorphism), they can return to a stable form once again. **Figure 13.5** demonstrates the recrystallization process in response to elevated temperature. In this example, the original grains are smaller and rounded, but recrystallization resulted in larger grains that become interlocking; the pore spaces are gone, and instead larger crystals exist.

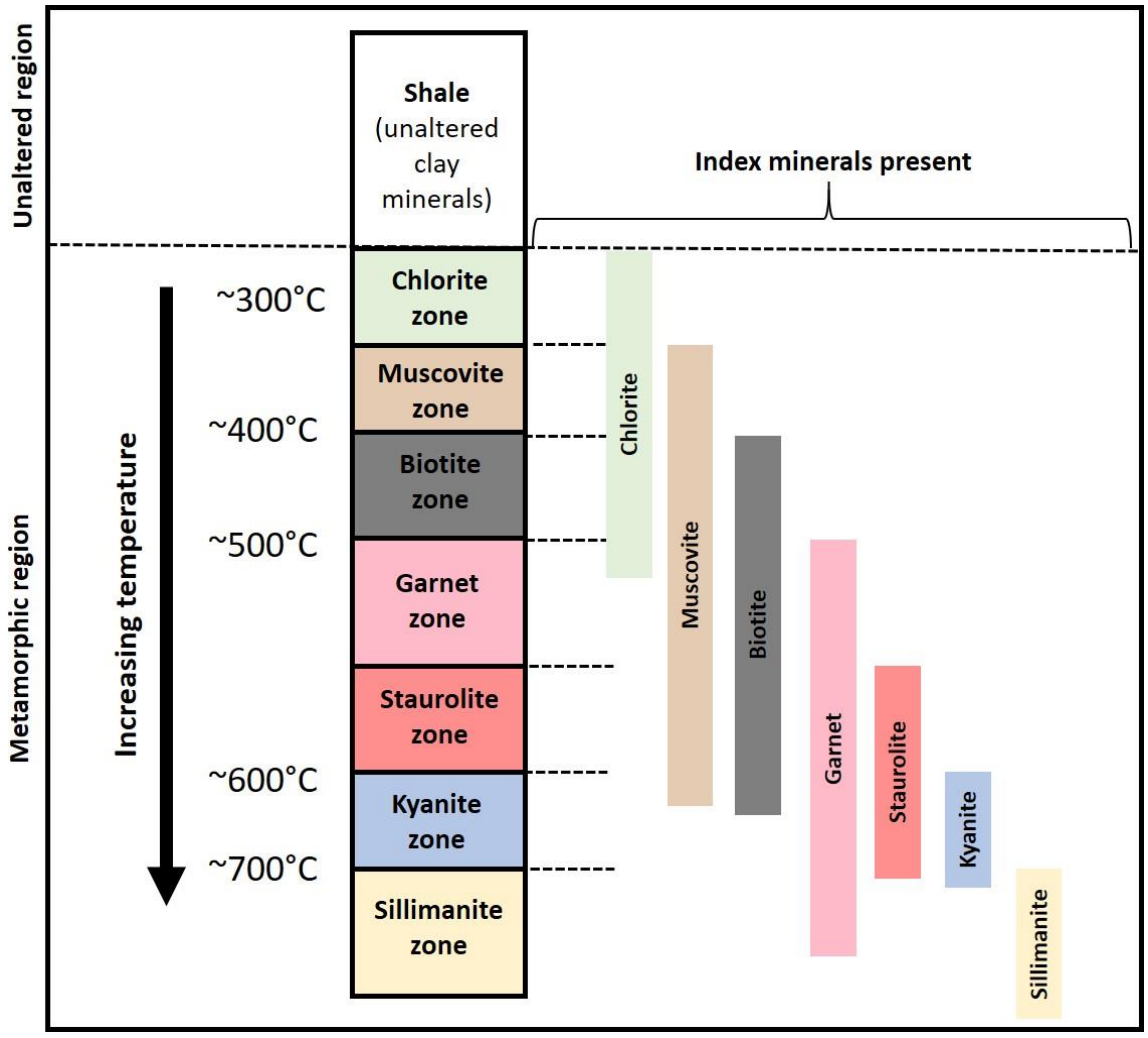


Figure 13.6: Different index minerals form depending on the amount heat and pressure the protolith undergoes.

In addition to increased grain size with increased temperature, occasionally a new mineral will form during metamorphism. These new minerals form at certain temperatures and are called **index minerals**, which can be used to determine the temperature of metamorphism (**Figure 13.6**).

Chemically Reactive Fluids

Higher temperatures are sometimes associated with metamorphism due to **chemically reactive fluids**. The phrase "chemically reactive" refers to the dissolved ions in a fluid phase that may react with minerals in a rock. These ions may take the place of some of the atoms in the mineral's structure, which can lead to a significant change in the chemical composition of a rock. Sometimes these fluids are quite hot, especially if they are fluids released from a nearby magma body that is crystallizing while cooling. Metamorphism due to such fluids is known as **hydrothermal metamorphism**. California's state rock, **serpentinite**, is formed during this process!

Attributions

- Figure 13.3: “Confining/Differential Pressure” (CC-BY 2.0; Emily Haddad, own work)
- Figure 13.4: “Foliation” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 13.5: Derivative of “Recrystallization” (CC-BY-SA 3.0; Karen Tefend via LibreText) by Chloe Branciforte
- Figure 13.6: “Index Minerals” (CC-BY 4.0; Chloe Branciforte, own work)

What Are Metamorphic Grades?

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 (**Figure 13.7**).

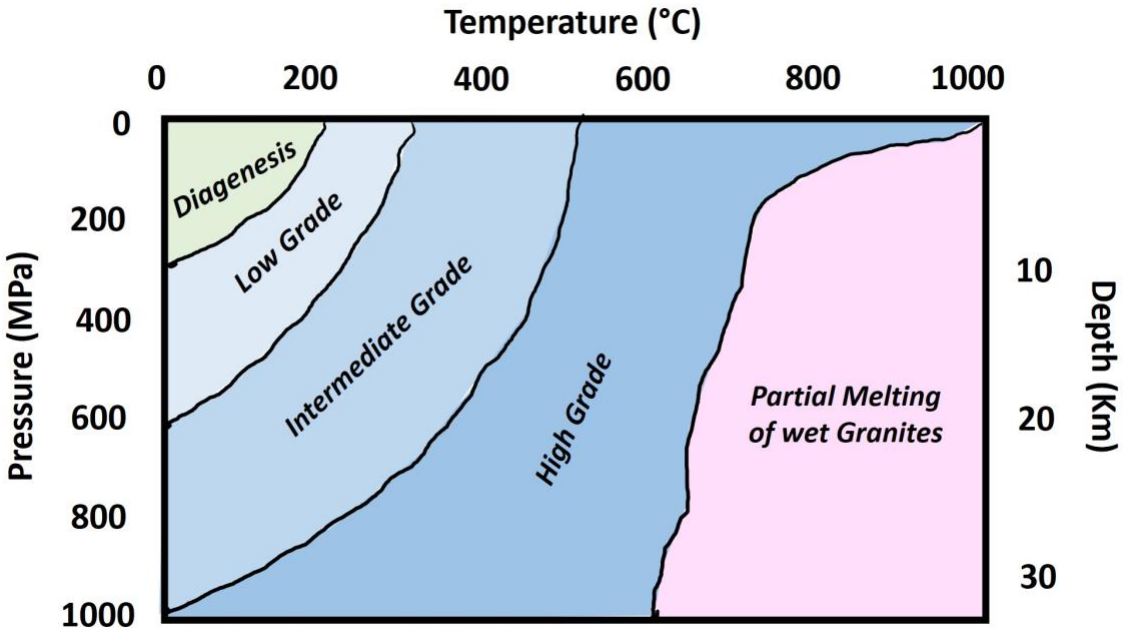


Figure 13.7: Metamorphic grades are categorized by the amount of heat and pressure.

Very Low and Low-grade metamorphism takes place at approximately 150–300°C and relatively low pressure. This is not far beyond the conditions in which sediments are lithified into sedimentary rocks, and it is common for a low-grade metamorphic rock to look similar to its protolith. Low-grade metamorphic rocks tend to be 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.

Intermediate-grade metamorphism takes place at approximately 300–450°C 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 now 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°C. Micas tend to break down. New minerals such as hornblende will form, which is stable at higher temperatures. As metamorphic grade increases to even higher grade, however, all hydrous minerals, including hornblende, may break down and be replaced by other, higher-temperature, non-hydrous minerals such as pyroxene.

Attributions

- Figure 13.7: “Metamorphic Grades” (CC-BY 4.0; Chloe Branciforte, own work)

How Do I Identify Metamorphic Rocks?

All metamorphic rocks are identified by their mineral content and texture. For metamorphic rocks, **texture** refers primarily to the orientation of the minerals in the rock. Additionally, crystal size can also convey important information regarding the temperature and pressure conditions during metamorphism.

To identify metamorphic rocks, you will first need to determine if the rock is **foliated** or **non-foliated**. Examine the rock for evidence of any pattern or foliation, and if present, identify the size and mineral(s) that compose the foliation pattern (**Figure 13.8, left**). Non-foliated metamorphic rocks can be identified by the properties associated with their dominant composition (**Figure 13.8, right**).

Figure 13.8: Left, a foliated metamorphic rock (Gneiss) which has organization and preferred orientation of mineral grains. Right, non-foliated metamorphic rock (Marble) which has no preferred orientation of mineral grains.

Attributions

- Figure 13.8: Derivative of “Gneiss 1” (CC-BY 2.0; James St. John via Flickr) and “Marble” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte

What Is a Foliated Metamorphic Rock?

Differential pressure typically results in the development of **foliation** in metamorphosed rocks. Metamorphic rocks have a variety of foliation examples; however, each is dependent on the minerals that define the foliation.

The most obvious is **gneissic banding**, which can be identified by the alternating dark and light mineral bands throughout the rock (**Figure 13.9**). The resulting metamorphic rock is called **gneiss** (pronounced "nice", with a silent g). These bands are not always flat but may be bent or folded and are still considered gneissic banding even though the bands are not horizontal. The typical minerals seen in the dark colored bands are biotite micas and amphiboles, whereas the light-colored bands are typically quartz or light-colored feldspars. The protolith for gneiss can be any rock that contains more than one mineral, such as shale with its clay minerals, or an igneous rock with both dark-colored and light-colored silicate minerals, like granite. For gneissic foliation to develop, temperatures and pressures need to be quite high; for this reason, gneiss represents a high-grade of metamorphism.

Figure 13.9: Gneiss with gneissic banding.

Sometimes a metamorphic rock is seen with mostly amphibole minerals that define the foliation pattern. The resulting rock is known as an **amphibolite**. Occasionally, amphibolites also have layers of light-colored plagioclase minerals present; in this case, the rock is known as an **amphibole gneiss**. Amphibolites may not always have a foliation. The protolith for an amphibolite is typically a rock with a large amount of dark silicate minerals, such as a mafic or ultramafic igneous rock. Amphibolites require higher temperatures and pressures to form and are also high-grade metamorphic rocks.

Metamorphic rocks with **schistose foliation** exhibit layering of platy minerals, such as muscovite or biotite micas. Differential stress forces the realignment of the micas, such that their cleavage faces are oriented in the same direction; this results in a rock that sparkles as light is reflected off its minerals' cleavage faces. The sparkly metamorphic rock is called **schist**, and typically the name will reflect which mica is present (**Figure 13.10**). By convention, when naming a metamorphic rock, the mineral in the lowest quantity is mentioned first: for example, garnet muscovite schist. The sedimentary rock shale is usually the protolith for schist; during metamorphism, the very tiny clay minerals in shale recrystallize into micas that are large enough to see unaided. Temperatures and pressures necessary for schistose foliation are not as high as those for gneiss and amphibolite; therefore, schists represent an intermediate-grade of metamorphism.

Figure 13.10: Left, mica schist. Right, garnet-mica schist. Notice the schistose foliation.

Metamorphic rocks with **phyllitic foliation** exhibit a layering of wavy platy minerals, such as muscovite or biotite micas; however, unlike schist, individual crystals are too small to be seen without magnification (**Figure 13.11**). The resulting metamorphic rock is called **phyllite**. Phyllite is a low-medium grade regional metamorphic rock in which the clay minerals and chlorite have been at least partly replaced by muscovite and biotite. This gives the surfaces of phyllite a

satiny or **phyllitic luster**, brighter than the surface of slate (**Figure 13.12**). 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.

Figure 13.11: The metamorphic rock phyllite. Note the phyllitic luster and foliation planes.

The last example of foliation, **slaty foliation (cleavage)**, is defined by the alignment of minerals too small to see, though foliation planes are still visible (**Figure 13.12**). The resulting metamorphic rock is called **slate**. Slate forms through low-grade metamorphism of a shale protolith. The clay sized minerals in the shale recrystallize into very tiny micas which are larger than the clay minerals yet still too small to be visible. Because these tiny micas are aligned,

however, they control how the slate breaks, and the rock tends to break parallel to the mica alignment. In certain rare instances, some fossils from the original shale may be preserved and visible in slate. Slate has great economic value in the construction industry; due to its ability to break into thin layers and impermeability to water, slate is used as roofing tiles and flooring. In addition to the construction industry, slate helped transform classrooms when the slate blackboard (or chalkboard) was introduced. Has anyone ever moved a pool table? They're so heavy because they are full of rock! Many have slate decks underneath the felt covering.

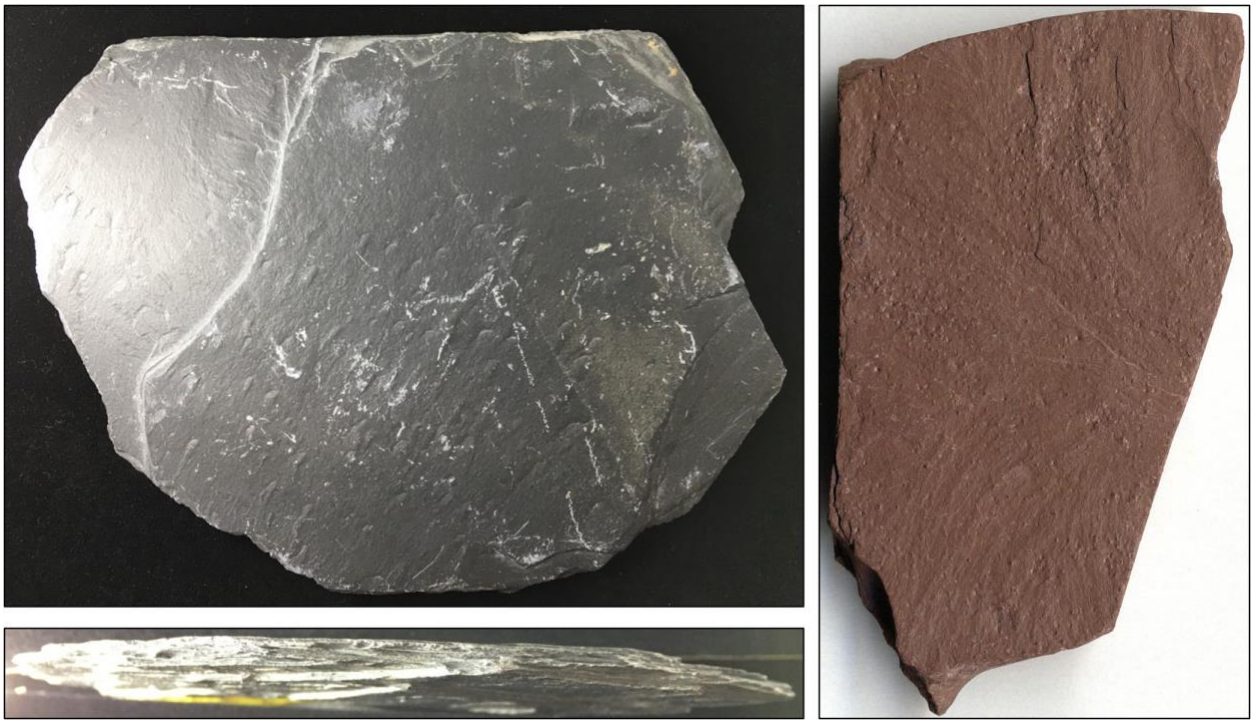


Figure 13.12: The metamorphic rock slate. Notice the slaty cleavage (bottom left).

Foliated Metamorphic Rocks			
Metamorphic Rock	**Grain Size**	**Metamorphic Environment & Grade**	**Protolith**
Slate	Very fine	Regional Very low, 150°C-300°C (300-570°F)	Mudrock, shale
Phyllite	Fine, with wavy layer and phyllitic luster	Regional Low, 300°C-450°C (570-840°F)	Mudrock, shale
Schist	Medium to coarse	Regional Intermediate, 450°C-550°C (840-1020°F)	Mudrock, shale
**Amphibolite Gneiss*	Coarse with light & dark bands	Regional High, >550°C (>1020°F)	Mudrock, granite, diorite, *basalt

Table 13.1: Foliated metamorphic rock chart.

Attributions

- Figure 13.9: Derivative of “Gneiss 1” (CC-BY 2.0; James St. John via Flickr) and “Gneiss 3” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte
- Figure 13.10: Derivative of “Mica Schist” (CC-BY 4.0; Chloe Branciforte, own work) and “Garnet Schist” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte
- Figure 13.11: “Phyllite” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 13.12: Derivative of “Gray Slate” (CC-BY 4.0; Chloe Branciforte, own work) and “Red Slate” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte
- Table 13.1: “Foliated Metamorphic Rocks” (CC-BY 4.0; Chloe Branciforte, own work)

What Is a Non-Foliated Metamorphic Rock?

Metamorphic rocks that lack foliation are referred to as **non-foliated**. This is primarily due to a lack of differential pressure involved during metamorphism. However, if the protolith rock is monomineralic (composed of one mineral type), such as limestone, dolostone, or sandstone, then a foliation will not develop even with differential pressure. *Why?* Calcite, dolomite and quartz sands are not platy minerals. These minerals will recrystallize into equant, coarse crystals, and the resulting metamorphic rock is named for its composition, not by foliation type.

Quartzite, is a metamorphic rock made almost entirely of quartz, for which the protolith was quartz sandstone (**Figure 13.13**). Because quartz is stable over a wide range of pressure and temperature conditions, few-to-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 in quartz sandstone. Colors will vary, and a hardness test must be done to

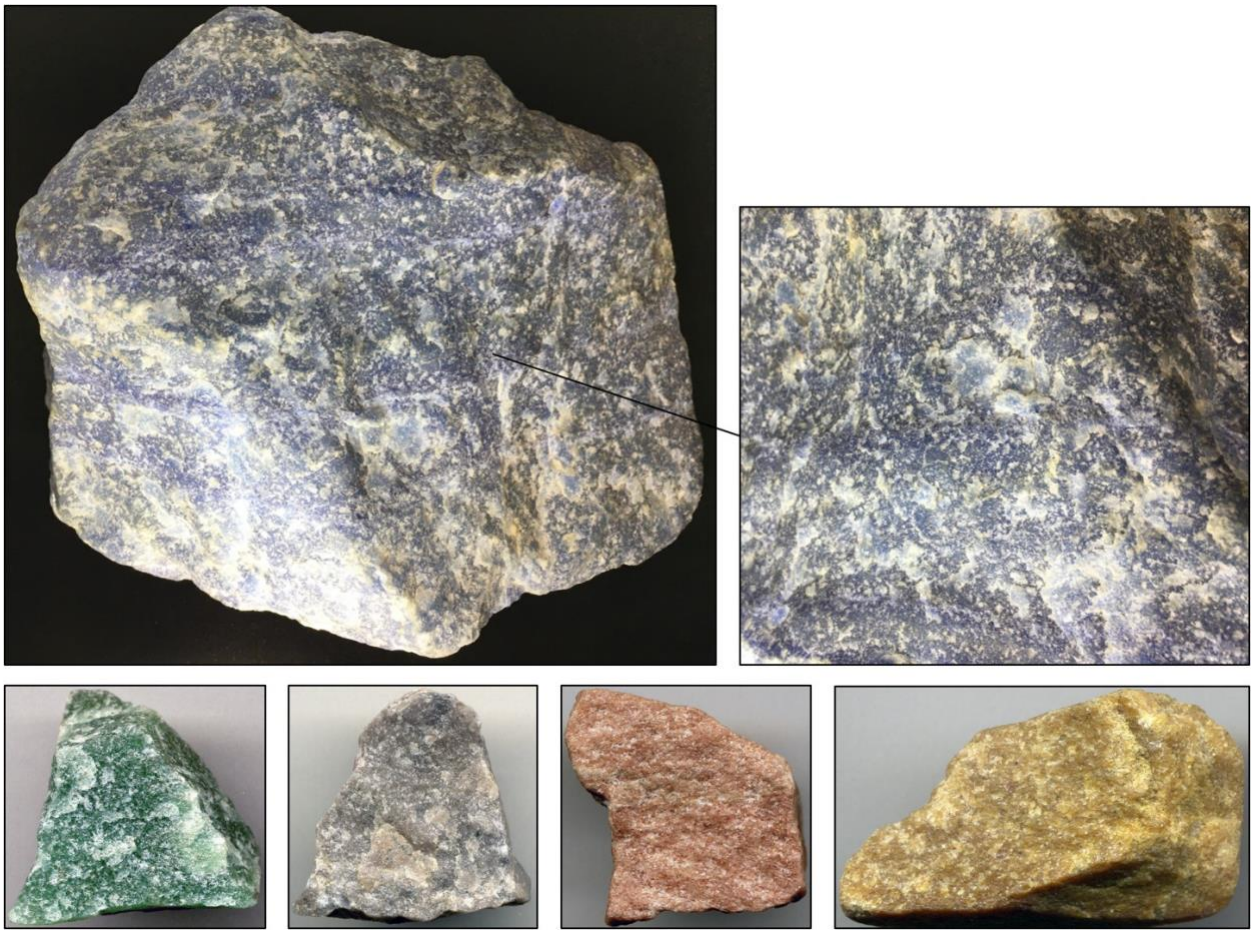


Figure 13.13: The metamorphic rock quartzite may be many colors. The blue quartzite at the top is from a locality in San Bernardino County, California.

be sure the sample is quartzite. Quartzite is fairly tough and will sometimes be used decoratively in building stone, facades, or for kitchen or bathroom countertops.

Marble is a metamorphic rock made entirely of calcite or dolomite, for which the protolith was limestone or dolostone (**Figure 13.14**). Marble may have bands of different colors which were deformed into convoluted folds while the rock was **ductile**. Marble will typically be soft, and can be scratched with a steel nail, and if there is enough calcite present, will react (effervesce, fizz, bubble) when HCl is added. Marble is also used as decorative stone in buildings, or in countertops in homes. Italy has the famous Carrera Marble mine, which many sculptors, including Michelangelo, used for their great works. Additionally, many older grave markers, particularly those that appear blank or heavily worn, are likely composed of marble.

Figure 13.14: White (*left*) and blue (*right*) marble. Blue marble from a locality in San Bernardino County, California.

Anthracite coal (**Figure 13.15**) is much harder than the coal varieties we discussed in the Sedimentary Rock chapter. It is black in color with a submetallic luster. Anthracite accounts for <1% of coal mined in the US with most mined from northeastern Pennsylvania; it is the highest grade of coal, with around 86%–97% carbon content, which makes anthracite a hotter burning coal. Under higher temperatures and pressures the protolith, bituminous coal, loses more volatiles (water vapor), but the carbon content is enriched. This metamorphism is not recrystallization, as coal is mostly organic remains; however, due to changes in temperature and pressure, bonds are still broken and reformed.

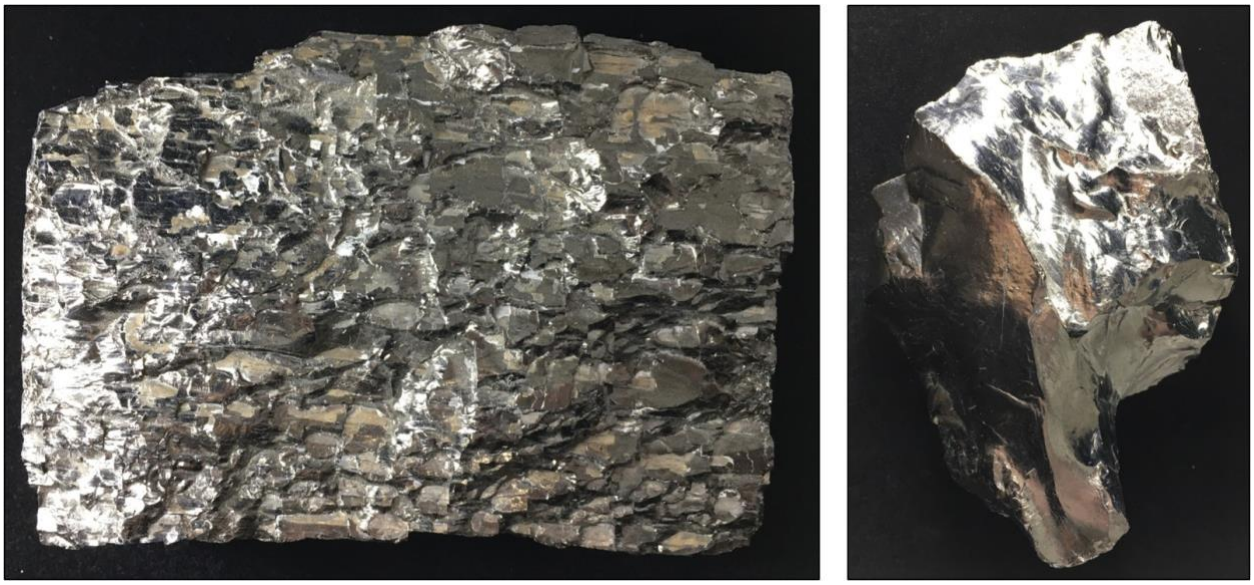


Figure 13.15: Anthracite coal. Notice the metallic luster of these samples.

Non-foliated Metamorphic Rocks			
Metamorphic Rock	**Dominant Composition**	**Metamorphic Environment & Grade**	**Protolith**
Quartzite	Quartz Test: scratches glass (H>5.5)	Contact intermediate to high	Sandstone
Marble	Calcite or Dolomite Test: Soft, will not scratch a copper piece (H=3); may react with HCl	Contact low to high	Limestone, dolostone
Anthracite	Carbon Test: Light heft, black color with a submetallic luster	Burial high	Bituminous coal

Table 13.2: Non-foliated metamorphic rock chart.

Attributions

- Figure 13.13: Derivative of “Blue Quartzite” (CC-BY 4.0; Chloe Branciforte, own work) and “Quartzite 3” (CC-BY 2.0; James St. John via Flickr) and “Quartzite 4” (CC-BY 2.0; James St. John via Flickr) and “Quartzite 1” (CC-BY 2.0; James St. John via Flickr) and “Quartzite 2” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte
- Figure 13.14: “White and Blue Marble” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 13.15: “Anthracite” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 13.2: “Non-foliated Metamorphic Rocks” (CC-BY 4.0; Chloe Branciforte, own work)

Metamorphic Rocks of California

Most **soapstones** lack foliation and contain the mineral talc with lesser amounts of chlorite, pyroxenes, micas, amphiboles, carbonates, and other minerals (**Figure 13.16**). Recall that talc feels greasy and is incredibly soft. These properties are retained in the rock, and you will be able to feel the soapy-ness of the sample as well as scratch it with your fingernail. Typically, soapstone forms at subduction zones where heat, hot fluids (water), and directed pressure metamorphose protoliths like peridotites, dunites, and serpentinites. Many of the soapstones in California are found in the Santa Catalina Schist on Santa Catalina Island and the Sierra Pelona Schist near Palmdale.

Figure 13.16: Soapstone. Notice the distinct pearly luster. Will feel soapy.

Serpentinite also lacks foliation and is composed mainly of minerals from the serpentine group (**Figure 13.17**). **Serpentinization** occurs at subduction zones where heat, hot fluids (water), and directed pressure metamorphose peridotite or dunite. The name serpentinite alludes to the rocks mottled green, snake-skin appearance. This rock is significant because it is **California's state rock**. Concentrations of serpentinite exist in the **Franciscan Complex**, Coast Ranges, the Trinity Ophiolite, portions of the Sierra Nevada and Klamath Mountains.

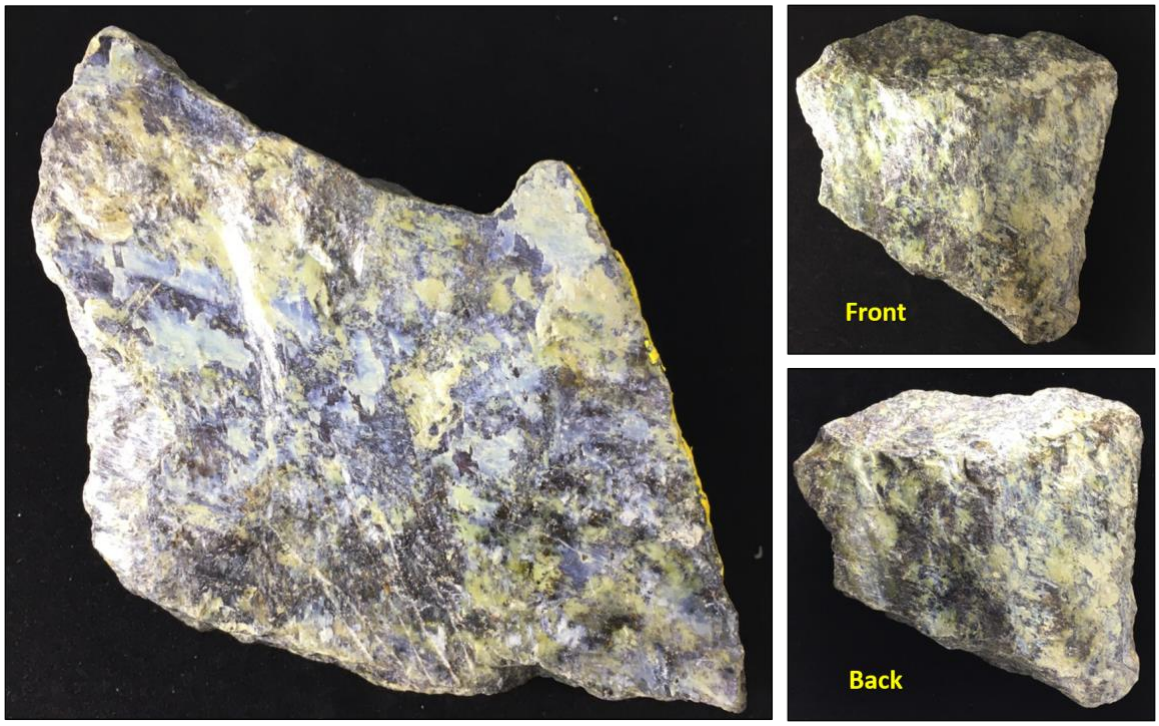


Figure 13.17: Serpentinite, California's state rock. Notice the mottled greenish-color.

At subduction zones, the oceanic crust is relatively cool in comparison to the mantle, especially along its sea-floor upper surface. The metamorphism that takes place here is unique, with high-pressure but relatively low-temperature conditions. At these locations a mineral called **glaucophane**, which is blue in color, forms. This mineral is an important component of the rock known as **blueschist** (**Figure 13.18**).

Figure 13.18: Blueschist from the Franciscan Complex near Jenner, California.

As blueschist continues to subduct, it will eventually transform into **eclogite** at a depth of approximately 35 km (22 miles) (**Figure 13.19**). The eclogite will continue to sink deep into the mantle, never to be seen again because the rock will eventually melt. In only a few places in the world, where the subduction process has been interrupted by some other tectonic process, has partially subducted blueschist rock returned to the surface. One such place is the area around San Francisco; the rock here is known as the **Franciscan Complex**.

Figure 13.19: Eclogite from the Franciscan Complex, near Valley Ford, California. This eclogite formed when oceanic crust was subducted and cooked underneath the North American continental lithosphere during the Late Jurassic (~155-158 mya).

Unique Metamorphic Rocks in California			
Metamorphic Rock	**Composition and Test**	**Metamorphic Environment & Grade**	**Protolith**
Serpentinite	Serpentine Patchy green, waxy appearance, might scratch glass (H3-6)	Regional - Subduction zone, Hydrothermal low to intermediate	Peridotite Dunite Serpentinite
Soapstone	Talc Soft (H=1), greasy feel; pearly luster	Regional - Subduction zone, Hydrothermal low to intermediate	Dunite Peridotite
Blueschist	Blue color	Regional - Subduction zone Low temperature, High pressure	Basalt Gabbro
Eclogite	Dense; may have garnet present; may be greenish in color	Regional - Subduction zone Low temperature, High pressure	Basalt Gabbro

Table 13.3: Chart of unique metamorphic rocks in California.

Attributions

- Figure 13.16: “Soapstone” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 13.17: “Serpentinite” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 13.18: “Blueschist” (CC-BY 2.0; James St. John via Flickr)
- Figure 13.19: “Eclogite” (CC-BY 2.0; James St. John via Flickr)
- Table 13.3: “Unique Metamorphic Rocks of California” (CC-BY 4.0; Chloe Branciforte, own work)

Other Metamorphic Rocks

If a metamorphic rock is heated enough, it can begin to undergo partial melting in the same way that igneous rocks do. The more felsic minerals (feldspar, quartz) melt, while the more mafic minerals (biotite, hornblende) do not. When the melt crystallizes again, the result is light-colored igneous rock interspersed with dark-colored metamorphic rock. This mixed rock is called **migmatite** (**Figure 13.20, left and left center**).

Metaconglomerate (**Figure 13.20, right center**) looks similar to conglomerate, although sometimes the clasts are deformed (stretched or elongated). The original cement has recrystallized and may be quite durable. Some metaconglomerates may exhibit weak foliation, forming similar to slate or phyllite.

Hornfels (**Figure 13.20, right**) is a fine-grained non-foliated metamorphic rock with no specific composition, although it commonly forms from the protolith shale or mudrock. It is typically produced via contact metamorphic in the metamorphic aureole.

Figure 13.20: *Left,* migmatite (x2) from the Precambrian of Anza Borrego State Park. *Middle right,* metaconglomerate, unknown locality. *Right,* hornfels from Genesse Valley, California.

Attributions

- Figure 13.20: Derivative of “Hornfels” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte

What Are the Different Metamorphic Environments?

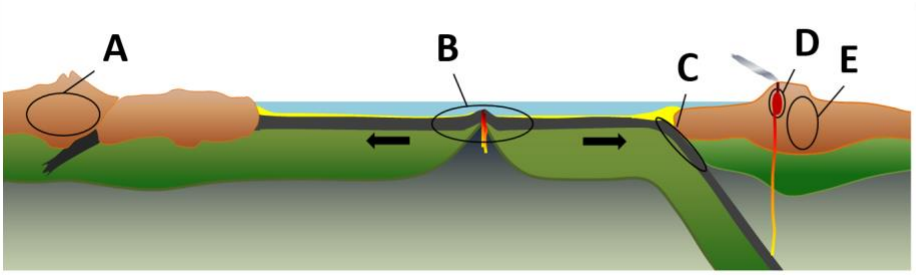
Metamorphic environments are areas or regions where metamorphic rock forms. These environments experience varying conditions – amounts of heat and pressure – which can transform a protolith in to a metamorphic rock.

Large-Scale Metamorphic Environments

Regional Metamorphism: Most **regional metamorphism** takes place within the continental crust and is commonly associated with convergent plate boundaries and the production of mountains. Regional metamorphism is common during continental-continental convergence, like that which is forming the Himalayan Mountains in Asia, and at subduction zones, like in the Pacific Northwest, and also characterized what-would-become-California during the Mesozoic Era as the Sierra Nevada Mountains were forming (**Figure 13.21, left**). Commonly, regional metamorphism will produce foliated metamorphic rocks because there is directional pressure; for example, a clay-rich protolith will respond to the pressure by converting the clay to mica, which aligns to produce foliation. Increased temperature will also increase grain size and encourage the development of new index minerals.

Burial Metamorphism: **Burial metamorphism** occurs when sedimentary rocks are buried to depths of several kilometers (more than a mile), and temperatures greater than 300°C (570°F). Burial metamorphism overlaps, to some extent, with **diagenesis**, and grades into regional metamorphism as temperature and pressure increase. To the unaided eye, metamorphic changes may not be apparent at all. Rocks like anthracite and metaconglomerate typically are formed in this environment.

Hydrothermal Metamorphism: A variety of regional metamorphism, **hydrothermal metamorphism** occurs in oceanic crust near divergent boundaries. Here, the rocks are affected by hot, chemically reactive fluids. Typically, soapstone and serpentinite are produced as a result of hydrothermal metamorphism.



Environments of metamorphism in the context of plate tectonics: **Cross-section of location D**
A) regional metamorphism related to mountain building at a continent-continent convergent boundary
B) regional metamorphism of oceanic crust in the area on either side of a spreading ridge
C) regional metamorphism of oceanic crustal rocks within a subduction zone
D) contact metamorphism adjacent to a magma body at a high level in the crust
E) regional metamorphism related to mountain building at a convergent boundary.

Figure 13.21: *Left,* environments of metamorphism in the context of plate tectonics: (A) regional metamorphism related to mountain building at a continent-continent convergent boundary, (B) regional metamorphism of oceanic crust in the area on either side of a spreading ridge, (C) regional metamorphism of oceanic crustal rocks within a subduction zone, (D) contact metamorphism adjacent to a magma body at a high level in the crust, and (E) regional metamorphism related to mountain building at a convergent boundary. *Right,* contact metamorphism.

Small-Scale Metamorphic Environments

Contact Metamorphism: **Contact metamorphism** occurs as the result of a temperature increase due to nearby magma body or lava flow. Recrystallization due to the increased temperature results in the formation of larger minerals, or sometimes in the formation of new minerals. The rocks closer in contact to the magma will form larger crystals due to the higher heat and may form high temperature index minerals such as garnet, staurolite, kyanite and sillimanite. The area surrounding the intrusion where the contact metamorphism effects are present is called the **metamorphic aureole** (**Figure 13.21, right**). Since differential pressures are not involved, contact metamorphism typically results in the formation of non-foliated rocks, like marble, quartzite, or hornfels.

Shock Metamorphism: While regional and contact metamorphism require significant time to pass for metamorphism to occur (up to several hundred thousand years), **shock (impact) metamorphism** takes place in a matter of seconds. This type of metamorphism occurs at the site of **impact craters**. Upon impact, the rocks in the vicinity are subjected to extreme stresses, and sometimes portions of these surface rocks become tiny blobs of melt that cool to form a type of glass called a **tektite**. Shock metamorphism is characterized by ultrahigh pressure

conditions and low temperature. The resulting minerals (such as coesite and stishovite) and textures are characteristic of these conditions.

Fault Zone Metamorphism: **Fault zone metamorphism** affects rocks along geologic faults which are deformed due to pressures associated with shearing, compression, or extensional stresses, with minor changes due to heat. Shallow faults, those close to the earth's surface and affected primarily by brittle deformation (<4 km or <2.5 mi), may grind the nearby rocks into smaller, angular fragments called **incohesive fault breccia**, or, if the breccia has been chemically altered, there may be a fine clay powder called **incohesive fault gouge** (**Figure 13.22**). Faults at depth, between 4-10 km (2.5-6 mi) will form cohesive fault breccia (cataclasite). Faults deeper than 10 km (>6 mi) will be affected by ductile deformation and **mylonite** is formed. The minerals in mylonitic rocks are deformed due to shear stresses associated with movement along the fault.

Figure 13.22: *Left,* San Andreas Fault Zone gouge, in southern California. *Right,* fault gouge sample from the San Andreas Fault Zone in California.

Attributions

- Figure 13.21: Derivative of “Hornfels” (CC-BY 4.0; Steven Earle via OpenText) and “Contact Metamorphism” (CC-BY-SA 3.0; Jillcurie via Wikipedia) by Chloe Branciforte
- Figure 13.22: Derivative of “Gouge Created by San Andreas Fault” (CC-BY 2.0; Michael R. Perry via Flickr) and “Fault Gouge” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte

Activity 14A: Identifying Metamorphic Textures

For this section you will need metamorphic rock samples selected by your instructor. Locate these samples before you begin.

1. Sample M1 has which metamorphic texture?
    a. Foliated
    b. Non-foliated

2. Is grain size or composition more important to identify Sample M1?
    a. Grain size
    b. Composition

3. What is the metamorphic rock name of sample M1?

4. Sample M1 is an example of:
    a. high-grade of metamorphism
    b. intermediate-grade of metamorphism
    c. low-grade of metamorphism

5. Identify a possible protolith for Sample M1.

6. Sample M2 has which metamorphic texture?
    a. Foliated
    b. Non-foliated

7. Is grain size or composition more important to identify Sample M2?
    a. Grain size
    b. Composition

8. What is the metamorphic rock name of sample M2?

9. Identify a possible protolith for Sample M2.

10. Sample M3 has which metamorphic texture?
    a. Foliated
    b. Non-foliated

11. Is grain size or composition more important to identify Sample M3?

- **a.** Grain size
- **b.** Composition

12. What is the metamorphic rock name of sample M3?

13. Identify a possible protolith for Sample M3.

14. Sample M3 is an example of:

- **a.** high-grade of metamorphism
- **b.** intermediate-grade of metamorphism
- **c.** low-grade of metamorphism

15. Sample M4 has which metamorphic texture?

- **a.** Foliated
- **b.** Non-foliated

16. Is grain size or composition more important to identify Sample M4?

- **a.** Grain size
- **b.** Composition

17. What is the metamorphic rock name of sample M4?

18. Identify a possible protolith for Sample M4.

Activity 14B: Interpreting Metamorphic Index Minerals

Use the figure below to answer the questions in this section.

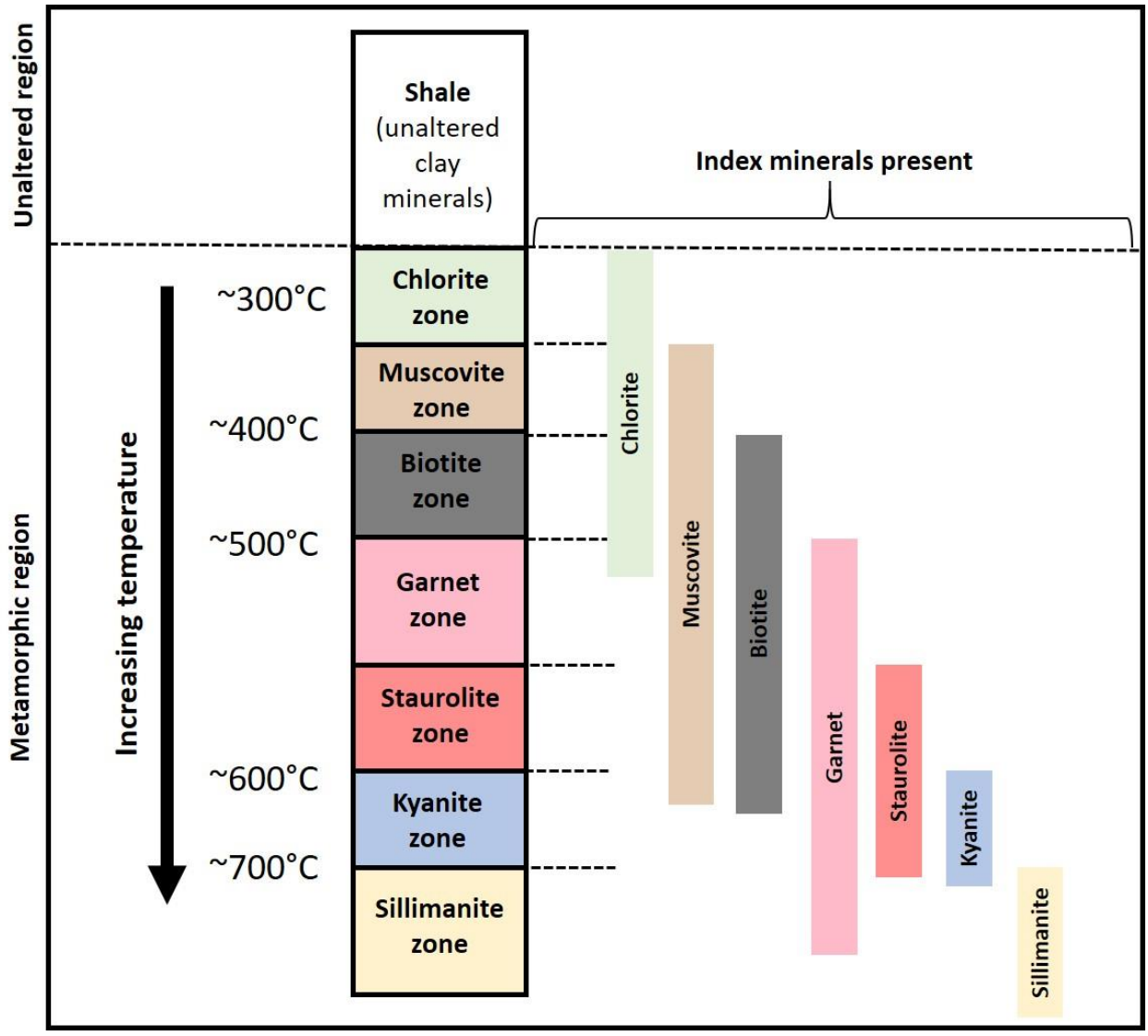


Figure 13.23: Different index minerals form depending on the amount heat and pressure the protolith undergoes.

1. The flat, platy minerals common in foliated metamorphic rocks are:
   - **a.** Amphibole
   - **b.** Calcite
   - **c.** Quartz
   - **d.** Mica
   - **e.** Serpentine

2. Which of the following minerals would likely be found in a high-grade metamorphic rock?
    - **a.** Chlorite
    - **b.** Muscovite
    - **c.** Biotite
    - **d.** Kyanite

3. Which of the following minerals would likely be found in a low-grade metamorphic rock?
    - **a.** Chlorite
    - **b.** Biotite
    - **c.** Garnet
    - **d.** Sillimanite

4. Which mineral is unstable in the staurolite zone?
    - **a.** Chlorite
    - **b.** Muscovite
    - **c.** Biotite
    - **d.** Garnet

5. Which index minerals will not be found together in the same rock?
    - **a.** chlorite and garnet
    - **b.** chlorite and kyanite
    - **c.** biotite and staurolite
    - **d.** biotite and muscovite

    WHY NOT?

Attributions

- Figure 13.23: “Index Minerals” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 14C: Determining Metamorphic Environments

For this portion of the lab, you will be using the browser version of Google Earth, and rock samples provided by your instructor.

1. Using the sample indicated by your instructor, this rock is most likely an example of:
    a. regional metamorphism
    b. contact metamorphism

    WHY?

2. Using the sample indicated by your instructor, this rock is most likely an example of:
    a. regional metamorphism
    b. contact metamorphism

    WHY?

3. Using the sample indicated by your instructor, this rock is most likely an example of:
    a. Regional - hydrothermal metamorphism
    b. contact metamorphism

    WHY?

4. Using the sample indicated by your instructor, this rock is most likely an example of:
    a. Regional - hydrothermal metamorphism
    b. contact metamorphism

    WHY?

Activity 14D: Exploring Metamorphic Environments in Google Earth

1. Type 8°56'22.3"N 126°55'54.3"E in the search bar of Google Earth. Zoom out to an eye altitude (Camera) of ~1700 miles. What type of metamorphism is likely in this area?

    a. shock metamorphism
    b. contact metamorphism
    c. regional metamorphism
    d. fault zone metamorphism
    e. burial metamorphism

2. The agents of metamorphism in this region, are most likely:

    a. chemically reactive fluids
    b. Temperature
    c. Pressure
    d. some combination of the agents of metamorphism

3. As a metamorphic petrologist, what evidence would you look for to determine the metamorphism type? Why?

4. Type 35°01'38.9"N 111°01'21.9"W in the search bar of Google Earth. Zoom out to an eye altitude (Camera) of ~12,000ft. What type of metamorphism is likely in this area?

    a. shock metamorphism
    b. contact metamorphism
    c. regional metamorphism
    d. fault zone metamorphism

5. As a metamorphic petrologist, what evidence would you look for to determine the metamorphism type? Why?

6. Type 35°16'30.1"N 119°49'34.7"W in the search bar of Google Earth. Zoom out to an eye altitude (Camera) of ~145 miles. What type of metamorphism is likely in this area?

    a. shock metamorphism
    b. contact metamorphism
    c. regional metamorphism
    d. fault zone metamorphism

7. As a metamorphic petrologist, what evidence would you look for to determine the metamorphism type? Why?

Activity 14E: Metamorphic Rock Identification

Use the metamorphic rock samples provided by your instructor for this section. If the rock is **foliated**, fill out the 2nd column, skip the 3rd, and move on to the 4th and 5th columns. If the rock is **non-foliated**, skip the 2nd column, fill out the 3rd, 4th and 5th columns.

Sample Number	**Is the rock foliated (F)? What is the grain size** *(very fine, fine, medium, coarse)* **Identify any index minerals present.**	**Is the rock non-foliated (NF)? What is the composition? Are minerals coarse or fine?**	**Metamorphic rock name**	**Identify metamorphic grade.** *low, intermediate, high* **Identify a possible protolith**

Attributions

- Table 13.4: “Metamorphic Rock Chart” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 14F: Google Virtual Field Trip: Serpentinite and Blueschist

If you'd like to learn more about serpentinite and blueschist, join this virtual Google Earth field trip from the American Geophysical Union (AGU). Streetcar 2 Subduction: Angel Island.

Chapter 14: Geologic Time

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Apply basic geological principles to determine the relative ages of rocks.
- ✔ Understand the importance and significance of unconformities.
- ✔ Use isotopic data to estimate the absolute age of a rock.
- ✔ Explain why an understanding of geological time is critical to both geologists and the public in general.

Thumbnail for Chapter 14:

Thumbnail: "Rainbow Basin" (Public Domain; Mark Wilson, Department of Geology, The College of Wooster via Wikipedia)

What Is Geologic Time?

The amount of time involved in carving a landscape, forming rocks, moving continents is an important scientific question. Different **hypotheses** about the age of the Earth offer drastically different perspectives of the workings of geologic events that formed and shaped the planet. For example, if geologic time is relatively short (less than a 100 million years) then catastrophic events would have been required to form the features we see on the surface of Earth; whereas vast amounts of geologic time (more than 100 million years) could have produced the slow, steady rate of change we observe around us today.

Examining geologic time, or deep time, can be challenging for humans, as it is difficult for us to imagine hundreds of millions or billions of years. Geologists have used a variety of methods to map major geologic events and their duration to reconstruct Earth's history during the last 4.54 billion years. Early geologists (naturalists) were able to piece together a progression of rocks through time to construct the original **Geologic Time Scale**, and geologists continue to update and make the timescale more accurate (**Figure 14.1**). Interested in more GTS? Visit this interactive time scale for more information!

<table>
<tr><th>Eon</th><th>Era</th><th colspan="2">Period</th><th>Epoch</th><th>Ma</th></tr>
<tr><td rowspan="19">Phanerozoic</td><td rowspan="6">Cenozoic</td><td colspan="2" rowspan="2">Quaternary</td><td>Holocene</td><td rowspan="2">0.012</td></tr>
<tr><td>Pleistocene</td></tr>
<tr><td rowspan="4">Tertiary</td><td rowspan="2">Neogene</td><td>Pliocene</td><td rowspan="2">2.58</td></tr>
<tr><td>Miocene</td></tr>
<tr><td rowspan="3">Paleogene</td><td>Oligocene</td><td rowspan="2">5.333
23.03</td></tr>
<tr><td>Eocene</td><td>33.9</td></tr>
<tr><td>Paleocene</td><td>56.0</td></tr>
<tr><td rowspan="3">Mesozoic</td><td colspan="2">Cretaceous</td><td></td><td>66.0</td></tr>
<tr><td colspan="2">Jurassic</td><td></td><td>145.0</td></tr>
<tr><td colspan="2">Triassic</td><td></td><td>201.3</td></tr>
<tr><td rowspan="8">Paleozoic</td><td colspan="2">Permian</td><td></td><td>251.9</td></tr>
<tr><td rowspan="2">Carboniferous</td><td>Pennsylvanian</td><td></td><td>298.9</td></tr>
<tr><td>Mississippian</td><td></td><td>358.9</td></tr>
<tr><td colspan="2">Devonian</td><td></td><td>419.2</td></tr>
<tr><td colspan="2">Silurian</td><td></td><td>443.8</td></tr>
<tr><td colspan="2">Ordovician</td><td></td><td>485.4</td></tr>
<tr><td colspan="2">Cambrian</td><td></td><td>541.0</td></tr>
<tr><td rowspan="3">Proterozoic</td><td rowspan="2">Neo-</td><td>Ediacaran</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">1000</td></tr>
<tr><td>Cryogenian</td></tr>
<tr><td>Meso-</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Paleo-</td><td></td><td></td><td></td><td>2500</td></tr>
<tr><td>Archean</td><td></td><td></td><td></td><td></td><td>4000</td></tr>
<tr><td>"Hadean"</td><td></td><td></td><td></td><td></td><td>4540</td></tr>
</table>

Figure 14.1: A modern geologic time scale.

Those who study geologic time can be associated with a variety of disciplines within geology, including sedimentology, paleontology, geomorphology, petrology, structural geology, and many others. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways are available in the private sector including in mining and natural resource extraction. Many of these career options require a college degree and postgraduate work. If you are interested, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible (chemistry is incredibly important for mineralogy). Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 14.1: “Geologic Time Scale” (CC-BY 4.0; Chloe Branciforte, own work)

How Do Geologists Measure Geologic Time?

This time scale was constructed by putting in order rock layers that had similar features, such as rock types, **environmental indicators**, or fossils. Scientists examined clues within the rocks and determined the comparative ages of these layers. This process is called **Relative Dating**, and helps geologists determine the relative age of one event from another. For example, knowing nothing else about you, I can guess that you are younger than your mother; your actual age doesn't matter if we can establish from independent evidence that someone, or some event, is older or younger than another.

As time progressed, scientists discovered and developed techniques to date certain rocks, including the age of the Earth itself. Geologists discovered the Earth was billions of years old (4.54 billion years old) and were able to establish a time frame for the Geologic Time Scale. This process is called **Absolute Dating**, which is the process of determining the exact amount of time that has passed since an object was formed or an event occurred.

Both absolute and relative dating have advantages and are still frequently used by geologists. Dating rocks using relative dating allows a geologist to reconstruct a series of events quickly, and can be used out in the field on a rocky outcrop. Relative dating also can be used on many different types of rocks, where absolute dating is restricted to certain minerals or materials. However, absolute dating is the only method that allows scientists to place an exact age to a rock.

Relative Time and Geologic Principles

The methods that geologists use to establish relative time scales are based on the **Geologic Principles**. Before we discuss the different geologic principles, it would be worthwhile to remind ourselves of the different rock types. **Sedimentary rocks**, like sandstone, are made from broken pieces of other rock that are eroded in higher elevations, transported by wind, water, ice, and gravity to lower areas, and deposited. The cooling and crystallization of molten rock forms **igneous rocks**. Lastly, the application of heat and pressure to rocks changes them into **metamorphic rocks**. This distinction is important because these three rock types are formed differently and therefore require different interpretations with respect to dating.

Uniformitarianism

The overarching principle of **Uniformitarianism** states that the Earth processes we observe today also occurred in the past and over long periods of time. This principle is often summarized as "the present is key to the past". This principle was originally based on the work of **James Hutton** and made popular by **Charles Lyell** in the 19th Century. Uniformitarianism was originally applied only to common, everyday geologic events, and excluded major catastrophic events like an asteroid impact. Many modern geologists will often instead use the term **actualism**, which examines how the universal physical laws govern both common *and* catastrophic events (**Table 14.1**).

	Catastrophism	Uniformitarianism	Actualism
Type of change	Big, sudden, events	Continuous, uniform, events	Both
Rate	Rapid, long ago	Constant	Rates vary; laws do not
Description	Begins, usually violently, then changes to something different.	Same events occur over time at same rate; "The present is key to the past"	Universal physical laws are constant; however, Earth may become different if conditions change.

Table 14.1: Comparison between catastrophism, uniformitarianism, and actualism.

Original Horizontality

Originally named the "Law of Original Horizontality" by Nicolas Steno in the 17th Century, the **Principle of Original Horizontality** states that undeformed sedimentary rocks are first

deposited horizontally. The deposition of sediment is controlled by gravity and will pull it downward. If you have muddy water on a slope, the water will flow down the slope and pool flat at the base rather than depositing on the slope itself. The implication is that, if a sedimentary rock layer is tilted or folded, it was first deposited flat then folded or tilted after lithification. In other words, sediments are deposited in horizontal layers; only after deposition does deformation occur (**Figure 14.2**).

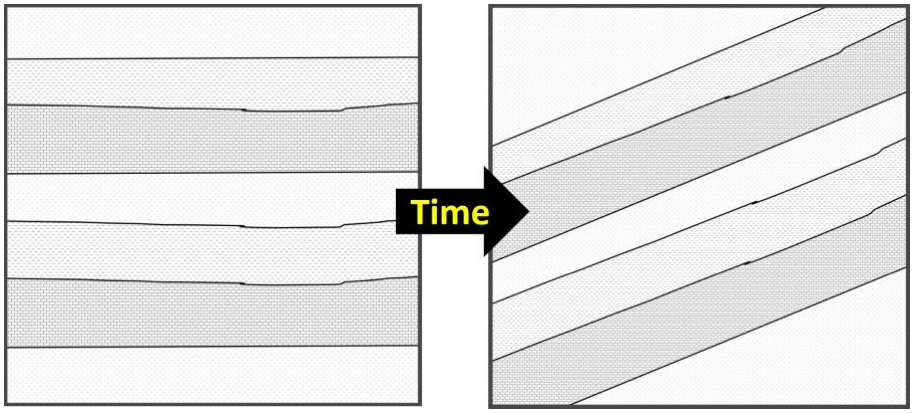


Figure 14.2: The principle of original horizontality states that undeformed sedimentary rocks are deposited horizontally (left). The rocks on the right have been tilted. This tilting event would have to occur after deposition of the horizontal layers.

Superposition

Originally named the "Law of Superposition" by Nicolas Steno, the **Principle of Superposition** states that, in an undeformed sequence of sedimentary rocks, the oldest rocks will be at the bottom of the sequence while the youngest will be on top. Imagine a river carrying sand into an ocean: the sand will spill out onto the ocean floor and come to rest on top of the seafloor. This sand was deposited after the sand of the seafloor was already deposited, and is therefore above it. We can envision a relative time scale of rock layers from the oldest rocks at the bottom (#1) to the youngest at the top of an outcrop (#7) (**Figure 14.3**).

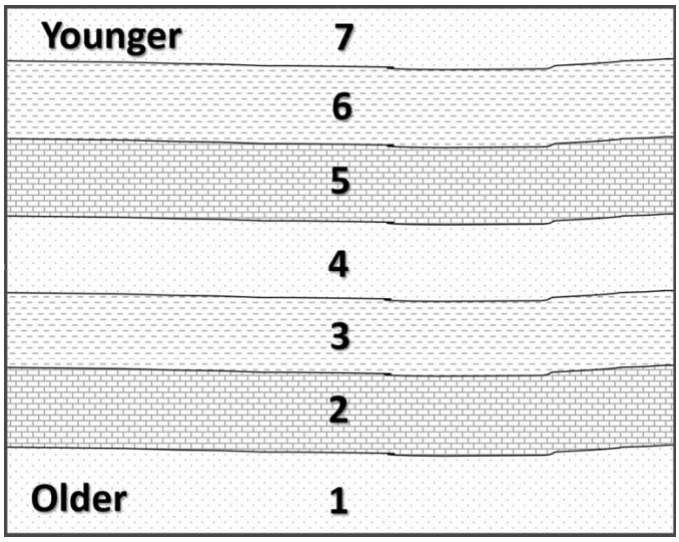


Figure 14.3: The principle of superposition states that in an undisturbed sequence of sedimentary rock, the oldest rocks will be found on the bottom, while the youngest will be located at the top.

Cross-Cutting Relationships

Originally named the "Law of Cross-cutting" by Nicolas Steno, the **Principle of Cross-Cutting Relationships** states that when two geologic features intersect, the one that cuts across the other is younger, or happened more recently. A feature must be present before something can affect it. For example, if a fault fractures through a series of sedimentary rocks, those rocks had to have existed before the earthquake that formed the fault (**Figure 14.4**).

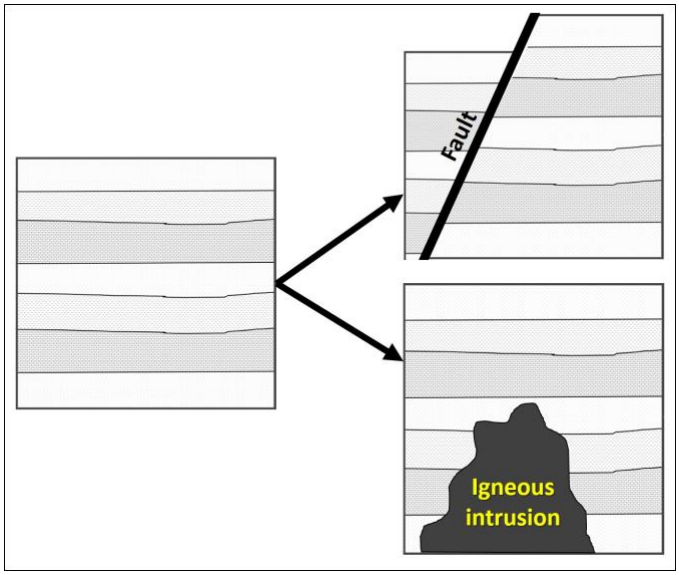


Figure 14.4: Block diagram showing the principle of cross-cutting relationships. The geological features (fault or Igneous intrusion) that cuts across the sedimentary layers must be younger.

Lateral Continuity

Originally named the "Law of Lateral Continuity" by Nicolas Steno, the **Principle of Lateral Continuity** states that layers of sediment, which lithify to form rock, form laterally extensive horizontal sheets. This means that the same type of sediment will be deposited across a landscape until the environment in which those sediments are deposited ends (e.g. beach sand will be deposited only in a beach environment) or until a physical barrier stops their deposition (e.g. river sediments are structurally confined to river channels). This is useful when correlating layers of rock across a landscape where erosion may have disrupted their continuity (**Figure 14.5**).

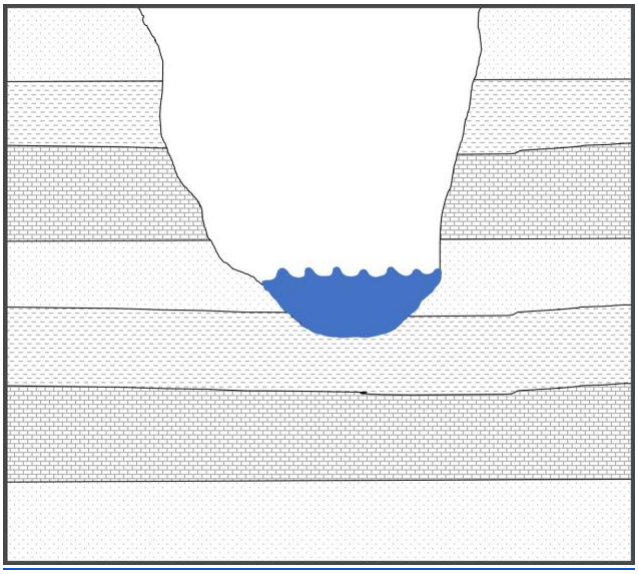


Figure 14.5: The principle of lateral continuity states that layers of sediment form laterally extensive horizontal sheets. The river, which has carved the valley, disrupted the continuity of the layers; however, we can match the rock on either side of the valley using this principle.

Faunal Succession

The **Principle of Fossil (Faunal) Succession** acts as an independent check to superposition and states that fossils succeed one another in known order. **Fossils** are the preserved remains of ancient organisms that are normally found within sedimentary rocks. Organisms appear at varying times in geologic history and go extinct at different times. These organisms also change in appearance through time. This pattern of the appearance, change, and extinction of thousands of fossil organisms creates a recognizable pattern of organisms preserved through geologic time. Therefore, rocks of the same age likely contain similar fossils and we can use these fossils to date sedimentary rocks. This principle was discovered by **William "Strata" Smith** as he worked to survey where the canals could be placed in England.

Certain fossils are particularly useful in telling time; these are called **index fossils**. These fossils are organisms that were abundant when they were alive, were widespread geographically, have hard parts (shell or skeleton), and have a limited geologic range (the amount of time an organism is alive on Earth). Index fossils are often the quickest and easiest way to date sedimentary rocks precisely and accurately (**Figure 14.6**).

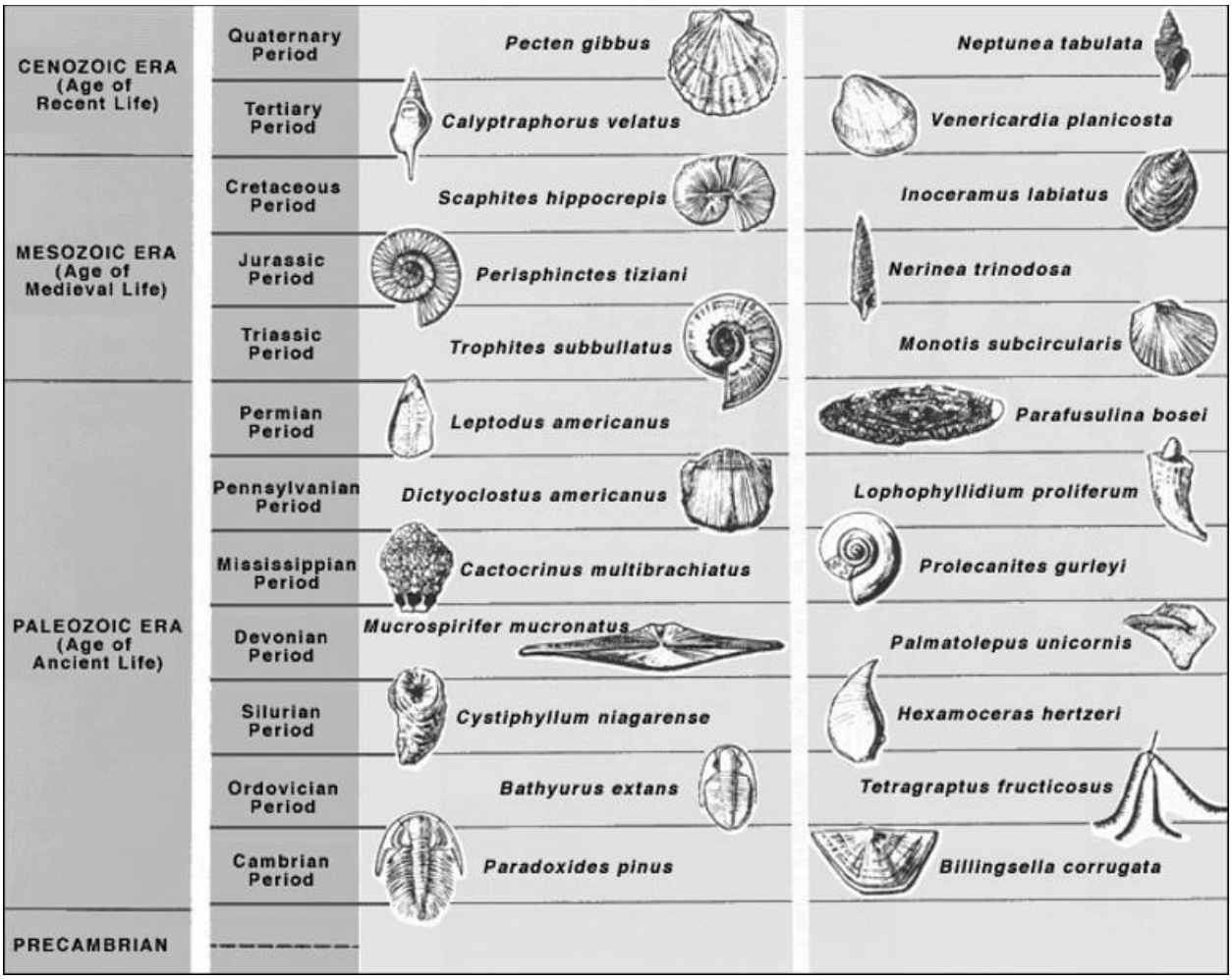


Figure 14.6: Keyed to the relative time scale are examples of index fossils, the forms of life which existed during limited periods of geologic time and thus are used as guides to the age of the rocks in which they are preserved.

Inclusions

The **Principle of Inclusions** states that any rock fragments (inclusions) that are included in a rock must be older than the rock in which they are included. For example, a **xenolith** in an igneous rock, or a clast in sedimentary rock, must be older than the rock that includes it (**Figure 14.7**).

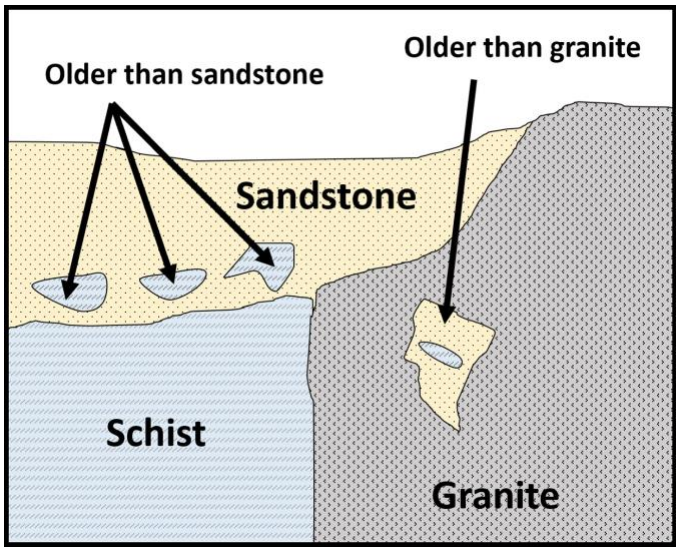


Figure 14.7: Block diagram showing the principle of inclusions, which states that inclusions are always older than the rock they are included within.

Baked Contacts

The **Principle of Baked Contacts** states that rock encountering molten rock, lava or magma, will become cooked or changed (metamorphosed). The presence of a baked contact indicates the igneous intrusion is younger than the rocks around it. If an intrusive igneous rock is exposed via erosion, then later buried by sediments, the surrounding rocks will not be baked, as the intrusion was already cold at the time of sediment deposition (**Figure 14.8**).

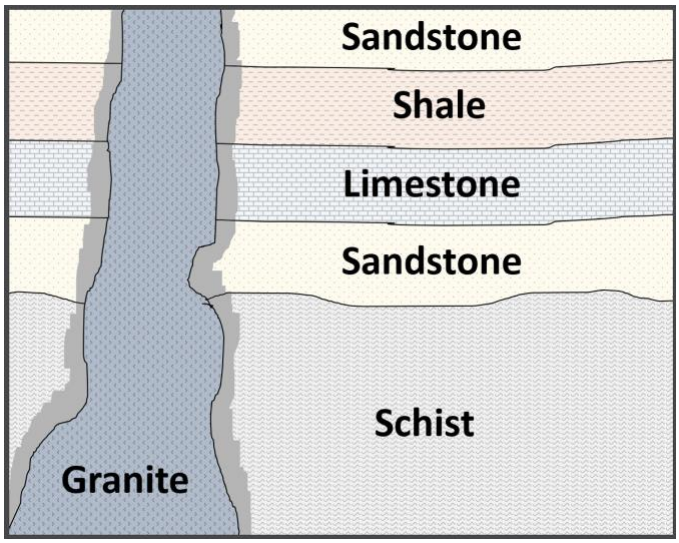


Figure 14.8: Block diagram showing the principle of baked contacts, which states that if a rock encounters a younger igneous event, whether intrusion or lava flow, the rock will become metamorphosed via contact with the younger molten rock.

Attributions

- Table 14.1: “Catastrophism, Uniformitarianism and Actualism” (CC-BY 4.0; Chloe Branciforte, own work)
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- Figure 14.3: “Superposition” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 14.4: “Cross-cutting” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 14.5: “Lateral Continuity” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 14.6: Derivative of “Index Fossils” (Public Domain; USGS) by Chloe Branciforte
- Figure 14.7: “Inclusions” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 14.8: “Baked Contacts” (CC-BY 4.0; Chloe Branciforte, own work)

Unconformities

The history of the Earth is written into strata in much the same way a book is written; occasionally, paragraphs are erased or pages are torn out. In order to fully understand the relative order in which a sequence of rocks formed, we need to know what is missing. Layers of rock or sediments can be described as having a conformable contact or an unconformable contact (unconformity) between them. A **conformable contact** represents unbroken deposition, with no hiatus (break or interruption in the continuity of the geologic record). The surface strata resulting are called a conformity (**Figure 14.9**).

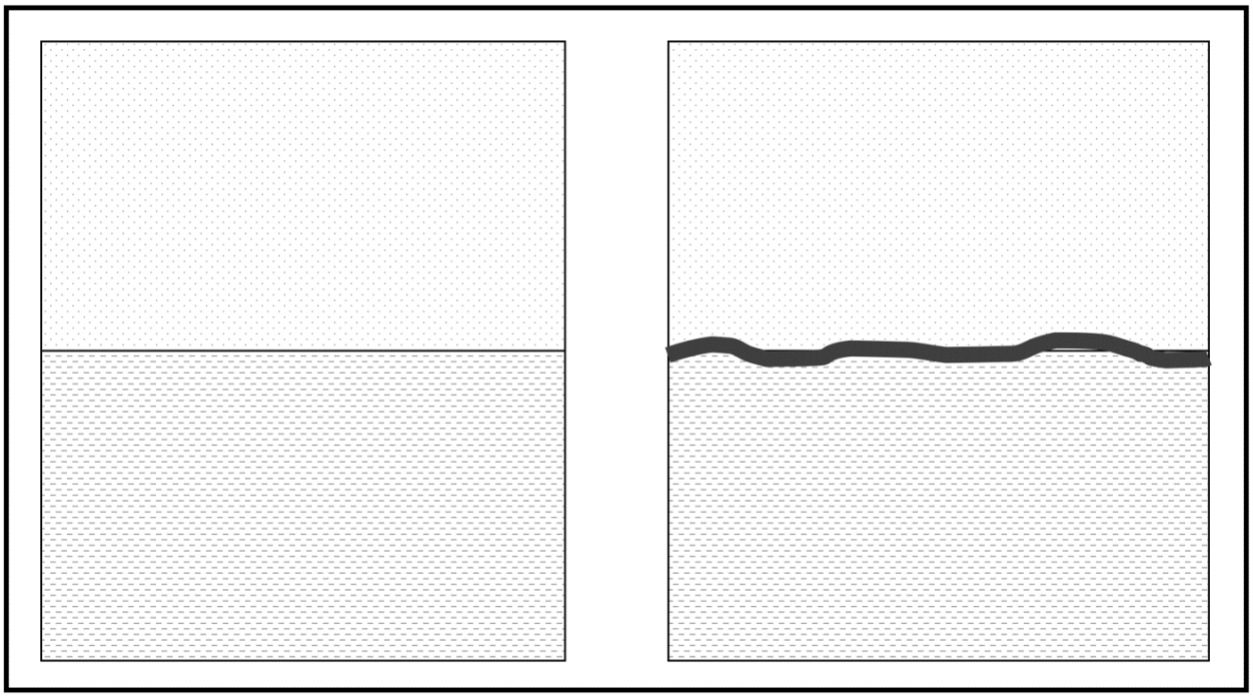

Figure 14.9: *Left*, layers (strata) with a conformable contact. *Right*, layers (strata) with an unconformable contact. The squiggly, dark line represents an unconformity.

An **unconformable contact** is a period of erosion or nondeposition. The resulting surface is called an **unconformity** (**Figure 14.9**), surfaces between **superjacent** bodies of rock that reflect missing pages or chapters of Earth history. A sea level fall (regression) may cause sedimentation to cease for a period, or uplift and erosion may remove large volumes of rock from a given region. The amount of time missing can be relatively short or may represent billions of years.

There are three types of unconformities:

1. An **angular unconformity** (**Figure 14.10**) is perhaps the easiest to recognize of the three types of unconformities. Angular unconformities occurs when there is a degree of angular

discordance between the layered rocks located above and below the plane of the unconformity. These angles form from tilting, folding, or other forms of deformation related to tectonic processes.

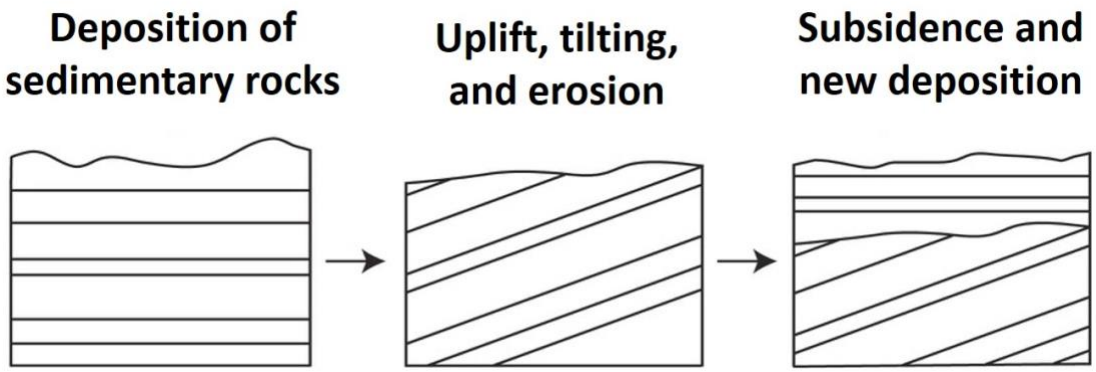

Figure 14.10: Block diagrams illustrating the formation of an angular unconformity.

2. A nonconformity (**Figure 14.11**) is where layered sedimentary rocks overlie an erosion surface developed on metamorphic or igneous rocks. Because the crystalline rocks that underlie nonconformities form deep in the crust were magmatism and regional metamorphism occur, the nonconformity reflects a period of tectonic mountain building followed by a prolonged period of regional erosion. You can remember *non*conformities because they form on top of *non*layered rocks.

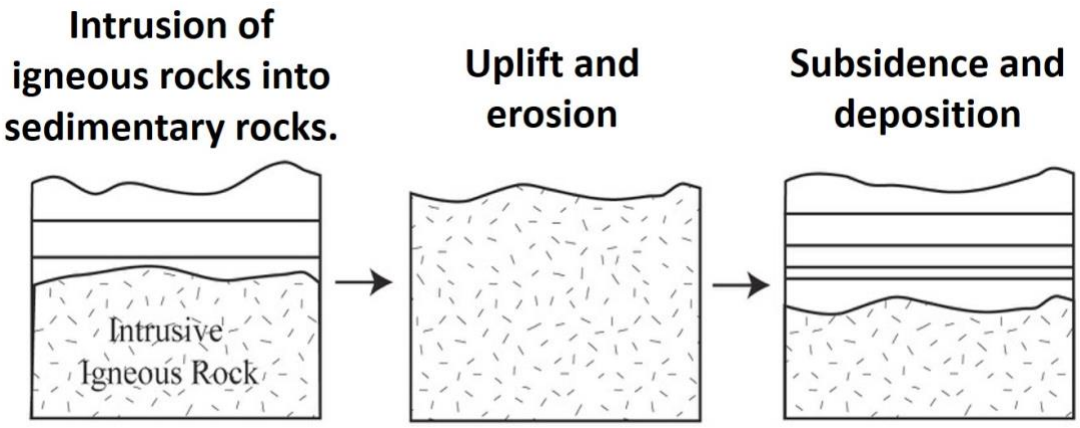

Figure 14.11: Block diagrams illustrating the formation of an angular unconformity.

3. A disconformity (**Figure 14.12**) is a surface of buried erosional relief between parallel layers of sedimentary rock. This makes disconformities more difficult to recognize in the rock record; frequently fossils are needed to determine the exact amount of geologic time missing between layers. Unfortunately, disconformities are fairly common in the rock record, as they frequently form as a result of the natural fluctuations in sea level.

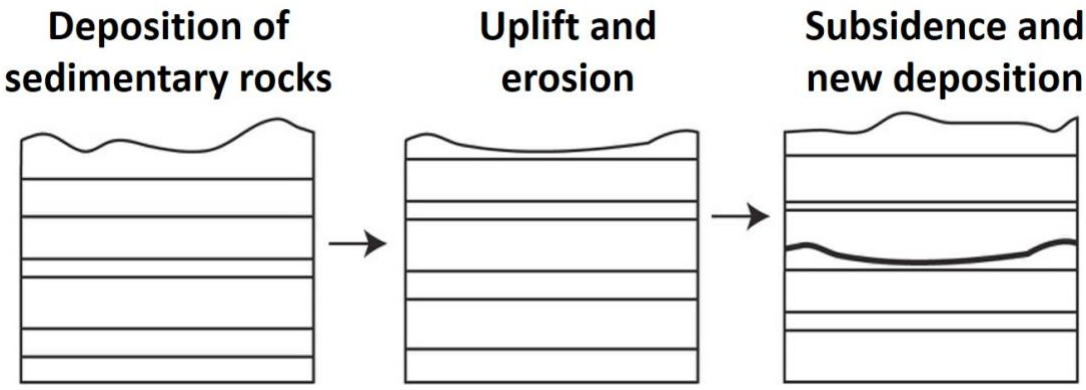

Figure 14.12: Block diagrams illustrating the formation of a disconformity.

Use this flow chart (**Figure 14.13**) to determine the unconformity types:

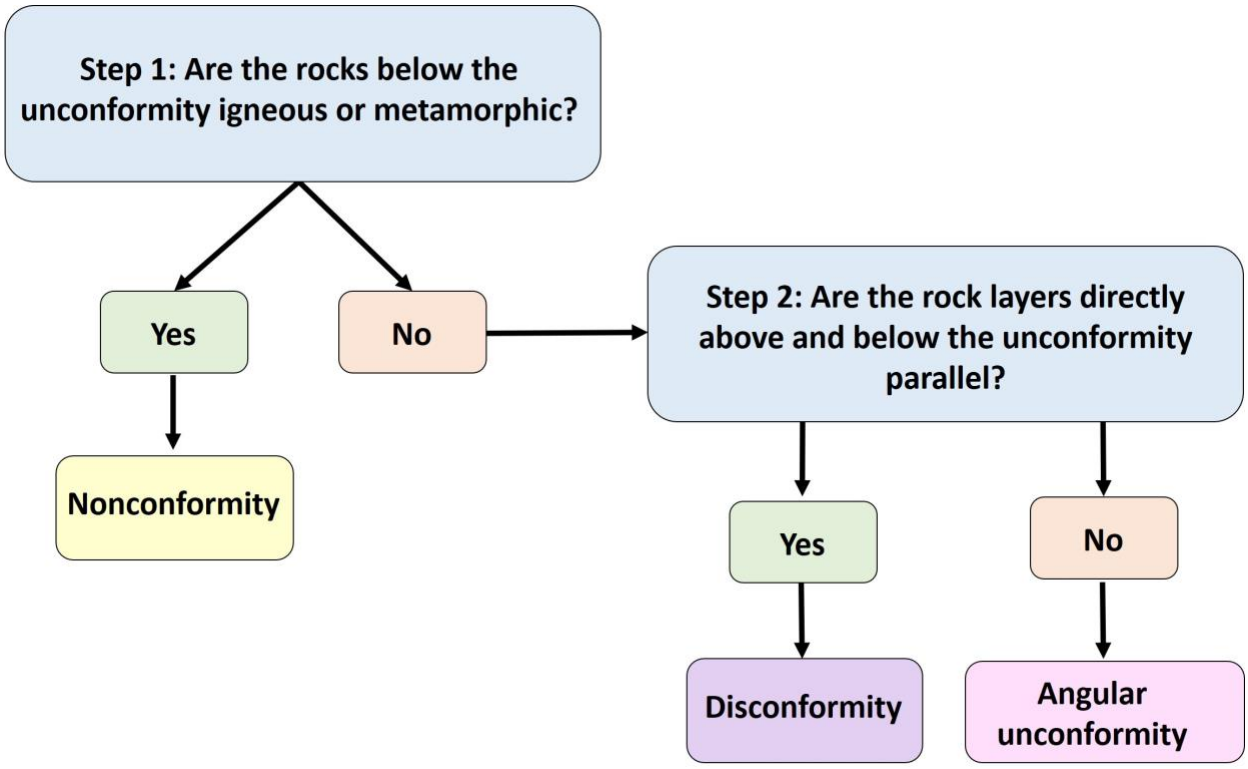

Figure 14.13: Block diagrams illustrating the formation of a disconformity.

Attributions

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- Figure 14.13: “Unconformity Flow Chart” (CC-BY 4.0; Chloe Branciforte and Kelli Wakefield, own work)

Applying the Geologic Principles to a Geologic History Diagram

Using these geologic principles, we can examine a series of rock layers and determine their relative ages and establish an order or series of events that must have occurred. Common events that are often recognized can include 1) Deposition of sedimentary layers, 2) Tilting or folding rocks, 3) Uplift and erosion of rocks, 4) Intrusion of liquid magma, and 5) Fracturing or breaking of rock (faulting). **Figures 14.14** and **14.15** show how to piece together a series of geologic events using relative dating.

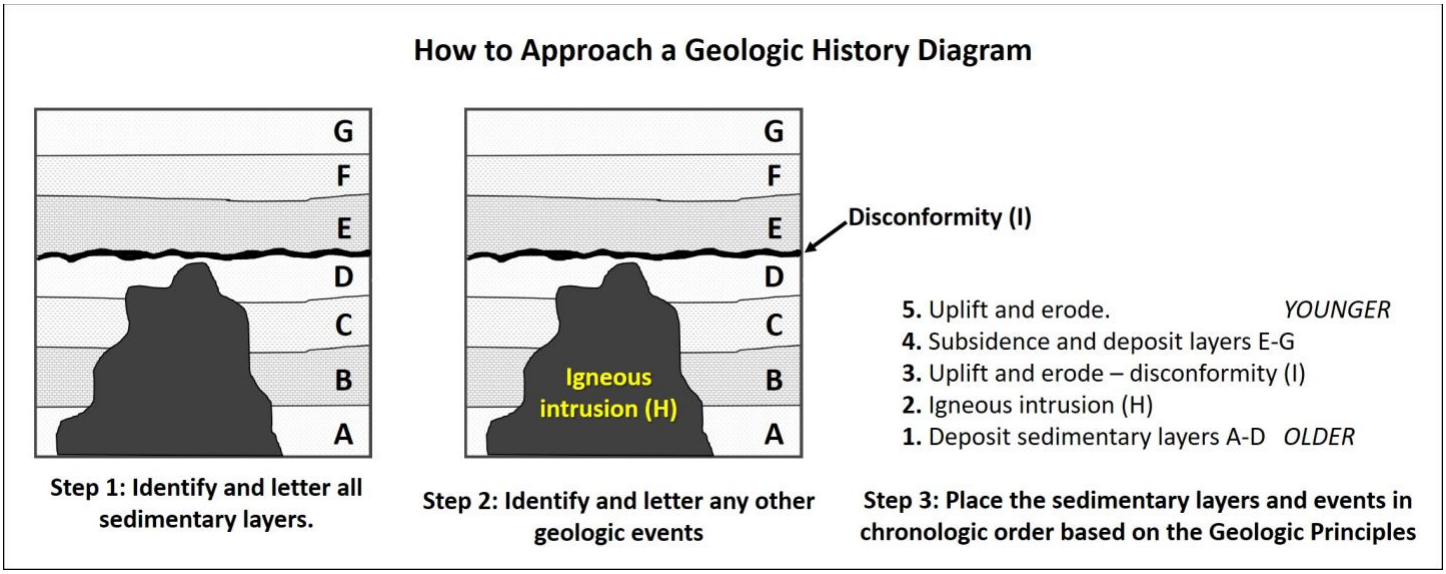

Figure 14.14: Steps to consider when approaching a geologic history diagram.

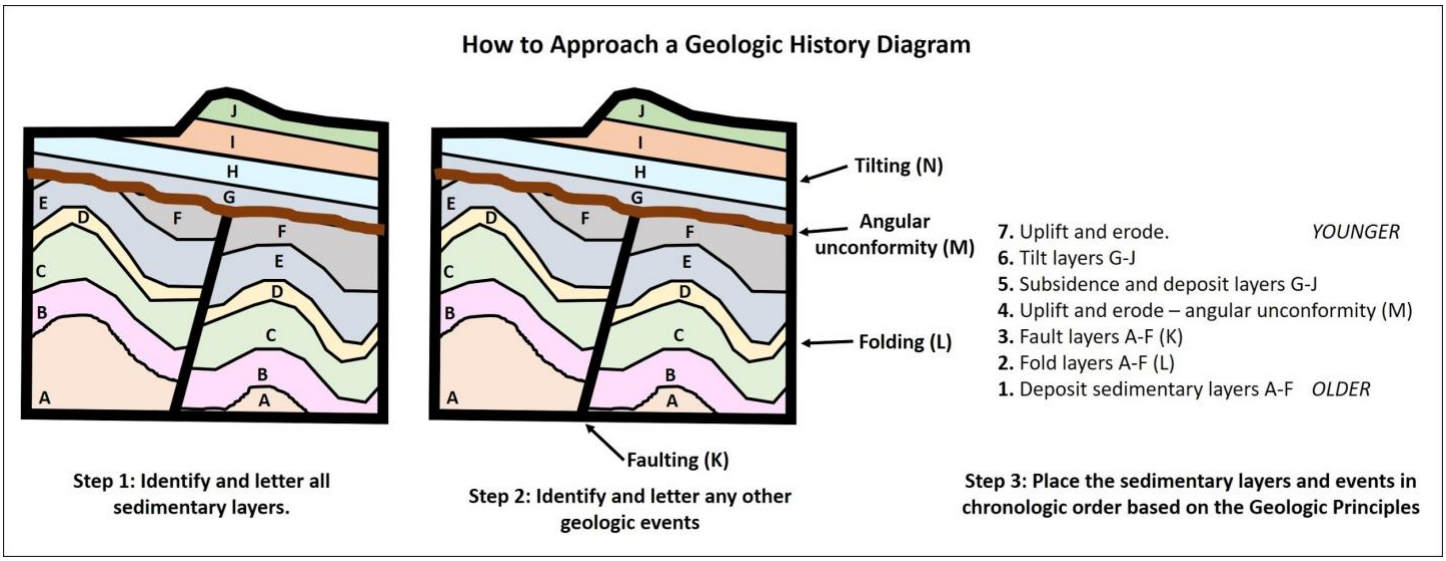

Figure 14.15: Steps to consider when approaching a geologic history diagram.

Attributions

- Figure 14.14: “How to Approach a Geologic History Diagram #1” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 14.15: “How to Approach a Geologic History Diagram #2” (CC-BY 4.0; Chloe Branciforte, own work)

Numeric Dating

Unlike relative dating methods, numeric (or absolute) dating methods provide specific numeric ages for rock layers and help measure the rates at which geologic processes operate. There are numerous scientific techniques to determine a numeric age. For example, we might date trees by counting the number of annual growth rings, using a science called **dendrochronology**. For geoscientists, however, the most used (and useful!) numeric dating technique is **radiometric or isotopic dating**. For this technique, radiometric isotopes are measured in rock samples. An **isotope** is an atom of an element with a different number of neutrons, and therefore different atomic weight; all elements on the periodic table have isotopes. If an atom has too many or too few neutrons in its nucleus, it becomes unstable and breaks down over time, through a process called **radioactive decay**.

CHEMISTRY THROWBACK: Atoms are made of three particles: protons, electrons, and neutrons. All three of these particles are important to geology. The number of protons defines an element, the number of electrons controls how that element bonds to make compounds, and the number of neutrons changes the atomic weight of an element.

The process of radioactive decay involves the emission of particles from a radioactive isotope – the **parent isotope** – until it loses enough neutrons, electrons, and protons until it changes into another, more stable, element – the **daughter isotope**. Scientists can measure the radioactivity of an isotope in the lab and calculate its **rate of decay**. Though the rate of decay of different isotopes can vary from milliseconds to billions of years, *all radiometric isotopes decay in a predictable way*.

Radiometric decay follows a distinct curve that is defined by a radiometric isotope's half-life. The **half-life** is defined as the amount of time it takes for half of the atoms of the radiometric parent isotope to decay to the daughter isotope. The half-life is independent of the number of atoms in a material at a given time; because of this, it takes the same amount of time to go from 100% of the parent isotope remaining to 50%, as it does to go from 50% of the parent isotope remaining to 25% (**Figure 14.16**).

If the length of the half-life for a radiometric isotope is known, and we measure the amount of parent and daughter isotope in a rock, we can then calculate the age of the rock. Given the shape of the decay curve, a material never runs out of the parent isotope completely; however, after around 10-15 half-lives the amount of the parent isotope left is so small that we are unable to effectively measure it. There are several different radiometric isotopes that are commonly used in absolute dating. Each of these systems has different uses within geology, because they require different materials and can date objects within different time frames.

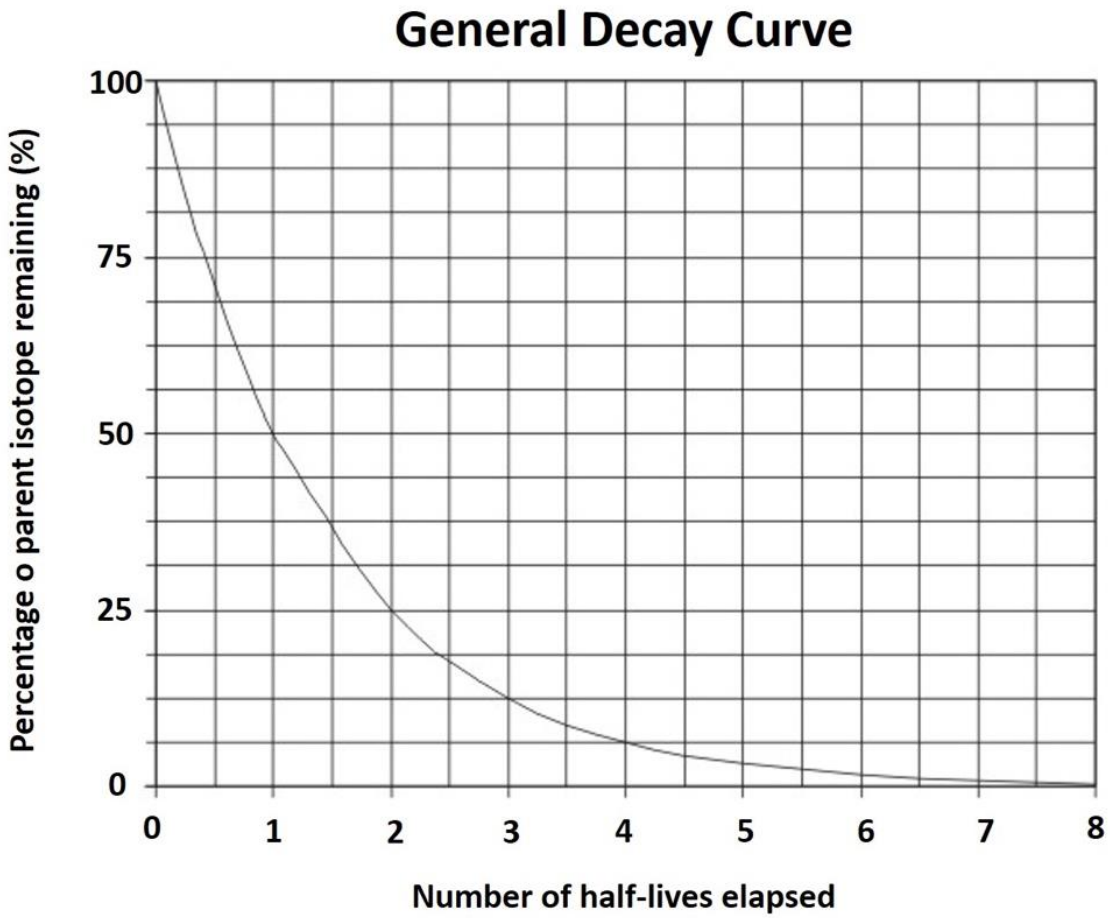

Figure 14.16: All radiometric isotopes decay in a predictable way. This decay curve illustrates the percentage of parent element is predictable at each half-life.

Carbon-14 dating, which may sound familiar to you, is actually of limited use within geology. Carbon-14 (the unstable parent isotope) is found in organic material like bone, tissue, plants, and fiber. This isotope is found naturally in small amounts in the atmosphere within CO_2 and is incorporated into plants during photosynthesis and then permeates through the food chain. You currently have carbon-14 in your body that is decaying to nitrogen-14 (daughter isotope), but you replace it whenever you eat. When an animal stops eating or a plant stops photosynthesizing (i.e. when they die), the radioactive carbon starts to decay without being replaced and can be easily measured. Carbon-14 has a very short half-life, only 5730 years, so it can only be used to date materials up to approximately 60,000 years in age. Given that the age of the Earth is 4.54 billion years, carbon-14 is not useful for dating materials from most of Earth's history.

For geology, we typically require isotopes with much longer half-lives (**Table 14.2**). Uranium dating involves a complex system of multiple isotopes that decay through a chain reaction until it reaches non-radiogenic lead. Uranium can be found naturally in many igneous rocks, notably the ubiquitous continental rock granite, but in very small amounts. Uranium-238 decays to lead-206, which is also found naturally in many different places; this can make it challenging to

differentiate between lead formed from radiometric decay and lead found naturally in the environment.

Common Half-life Pairs Used in the Geosciences				
Parent isotope	**Daughter isotope**	**Half-life**	**Dating range**	**Comments**
Potassium-40	Argon-40	1.3 Ga	10 ka-4.57 Ga	Widely applicable because most rocks have some potassium. Found in Muscovite, Biotite, Hornblende, and whole volcanic rock.
Uranium-238	Lead-206	4.5 Ga	1 Ma-4.57 Ga	The rock must have uranium-bearing minerals. Found in Zircon, and Uraninite.
Rubidium-87	Strontium-87	47 Ga	10 Ma-4.57 Ga	Less precision than other methods at old dates. Found in Muscovite, Biotite, Potassium feldspar, whole igneous or metamorphic rock
Carbon-14	Nitrogen-14	5,730 years	100-60,000 years	Found in wood, charcoal, peat, bone & tissue, shell or other calcium carbonate, groundwater, ocean water, glacier ice. Can be applied to young sediments.

Table 14.2: Common half-life pairs used in the geosciences.

The mineral zircon (**Figure 14.17**) solves both issues, by concentrating uranium and excluding lead from its mineral structure. Therefore, we use Uranium dating on zircons found within igneous rocks (such as volcanic ash or rocks formed deep in the earth). Uranium has a very long half-life of 4.57 billion years, which is more than long enough to date most rocks on Earth.

Potassium-Argon dating is also a useful method of dating rocks. Potassium decays into two separate daughter isotopes, argon and calcium. Geologists will measure the amount of argon, a noble gas, in minerals because, unlike calcium, it is rare and does not normally bond with other elements. Therefore, we can be sure that any argon within a mineral is from the decay of potassium. The use of argon also

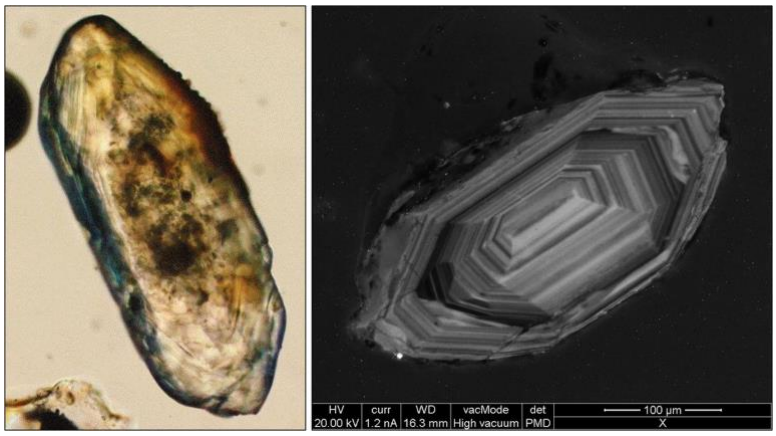

Figure 14.17: Zircon grains under different magnifications.

has its drawbacks; for instance, a gas can easily escape from a rock and, therefore, special care needs to be taken in the lab to prevent this. This system works well when there are multiple materials to examine that contain abundant potassium, like the rock granite that is full of the potassium-rich pink feldspars. The half-life of potassium is 1.3 billion years, so, like uranium, it is most useful for dating older rocks.

With all these methods there is still the chance for error such that it is best to think of any particular radiometric date as a scientific hypothesis that needs to be further tested. Typically, numerical dates are reported with a +/- error bar. Error can come from the inclusion or loss of parent or daughter isotopes in the rock following its formation. This can happen for several reasons, most commonly because of heat and pressure (metamorphism). There are ways to correct for these issues that allow scientists to date both the rock and the metamorphic event as long as the geologic history is known. Improvements in technology continue to provide geologists with more precise instrumentation, resulting in more accurate numerical ages. This means every few years a new Geologic Time Scale is produced to accurately reflect ongoing research. This is the most recent timescale available from The Geological Society of America. As you examine the timescale, it might be useful to refer to common unit terminology for isotopic dating (**Table 14.3**).

Unit Terminology for Isotopic Dating		
Ga	Giga annum	billion years
Ma	Mega annum	million years
ka	kilo annum	thousand years

Table 14.3: Common unit terminology for isotopic dating.

It is improbable to find a rock that contains the exact number of remaining parent isotopes that falls exactly on one of the half-lives. In most cases, we need to use a simple formula to calculate the age of a rock using the length of the half-life and the amount of parent remaining. The formula is:

$$\text{Age} = -\left(\frac{t_{\frac{1}{2}}}{0.693}\right) ln\,(p)$$

$t_{\frac{1}{2}}$ = The length of the half-life in years

P = The amount of the parent remaining in decimal form. For example, if there is 50% of the parent remaining it would equal 0.5.

Let's work an example using the above equation; we can be sure we are using the equation correctly because we will already know the answer to in advance. Say you have a sample of

bone that has 25% of the Carbon-14 (half-life= 5,730 years) remaining; how old is the sample? We can answer this question in two ways:

1) We know that if there is 25% remaining, two half-lives have passed and since each half-life represents 5730 years, the bone would be 11,460 years old.
2) We could use the above equation and insert both the length of the half- life and the amount of the parent remaining:

$$\text{Age} = -\left(\frac{5730}{0.693}\right) ln\ (0.25)$$

To solve the equation, take the Natural Log (ln) of 0.25 and multiply by the term in the parentheses (make sure to include the negative sign). If you do this, you should get 11,460 years as well.

Attributions

- Figure 14.16: Derivative of “Radioactive Decay” (CC-BY-SA 3.0; Kurt Rosenkrantz via Wikimedia Commons) by Chloe Branciforte
- Table 14.2: “Common Half-life Paris Used in the Geosciences” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 14.17: Derivative of “Zircon Microscope” (CC-BY-SA 3.0; Denniss via Wikipedia) and “M0096D 024 ”(CC-BY-SA 4.0; ManuRoquette via Wikimedia Commons) by Chloe Branciforte
- Table 14.3: “Unit Terminology for Isotopic Dating” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 13A: Relative Dating and Geologic History Diagrams

Relative dating is an important tool for geologists to reconstruct a series of events quickly, especially in the field. In the following section, apply what you have learned regarding relative time to the questions below.

1. In **Figure 14.18**, which rock layer is the oldest?

2. Which Geologic Principle(s) did you use to conclude this ordering?

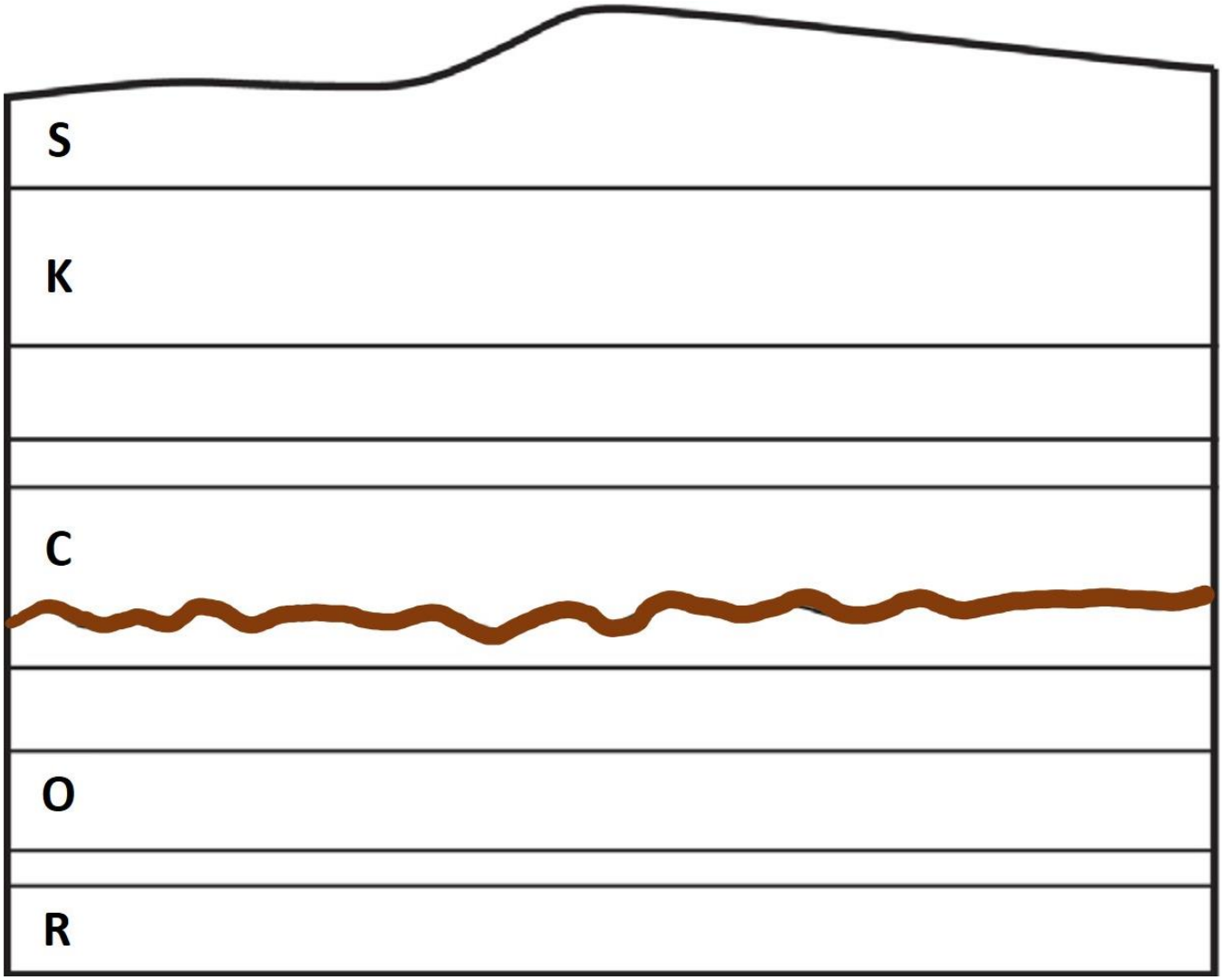

Figure 14.18: Block diagram for Questions 1 and 2 of Activity 13A.

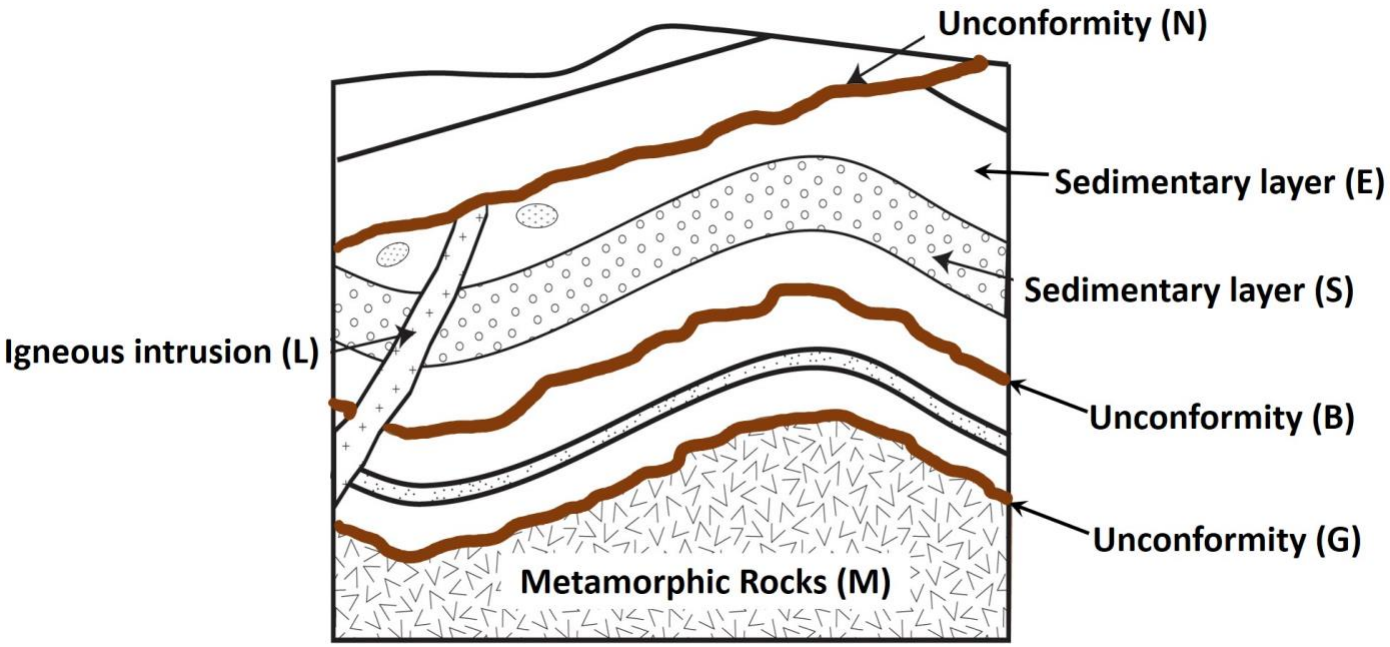

Figure 14.19: Block diagram for Questions 3-7 of Activity 13A.

3. In **Figure 14.19**, which of the letters is the youngest?

4. In **Figure 14.19**, which of the letters is the oldest?

5. Which Geologic Principle(s) did you use to help determine this?

6. Examine Unconformity G. What type of unconformity is this?

a. How were you able to determine this?

7. Examine Unconformity B. What type of unconformity is this?

a. How were you able to determine this?

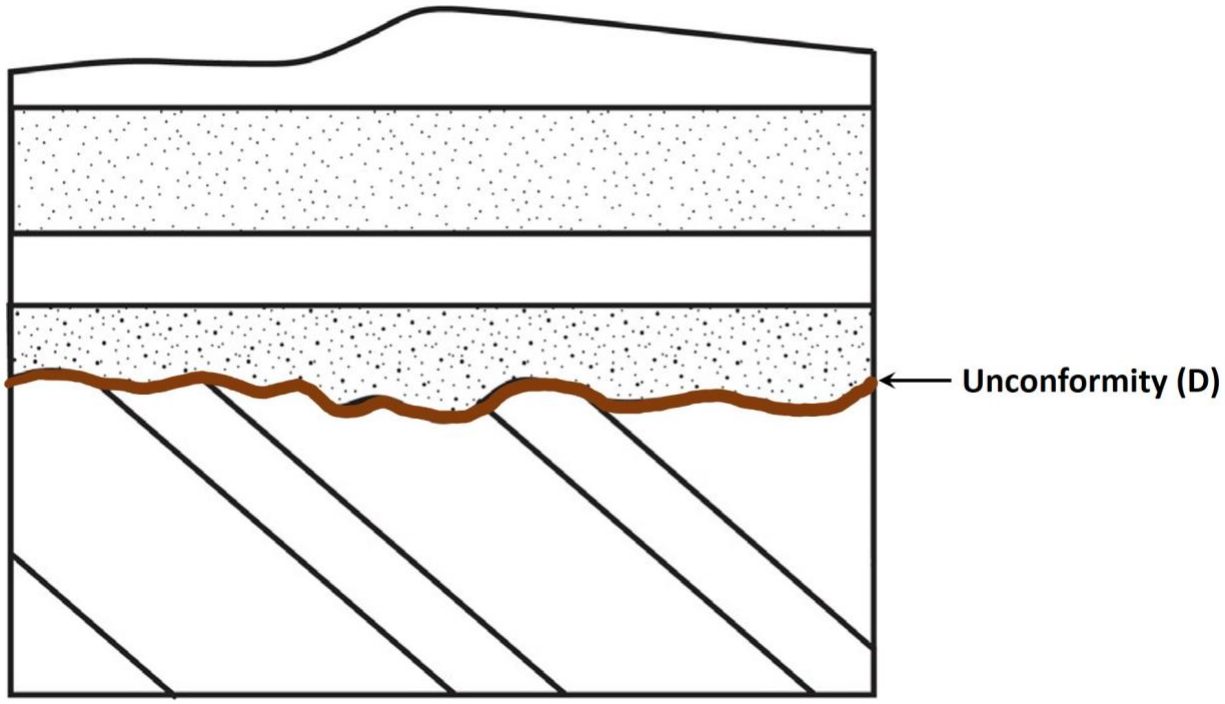

Figure 14.20: Block diagram for Question 8 of Activity 13A.

8. Examine Unconformity D in **Figure 14.20**. What type of unconformity is this?

a. How were you able to determine this?

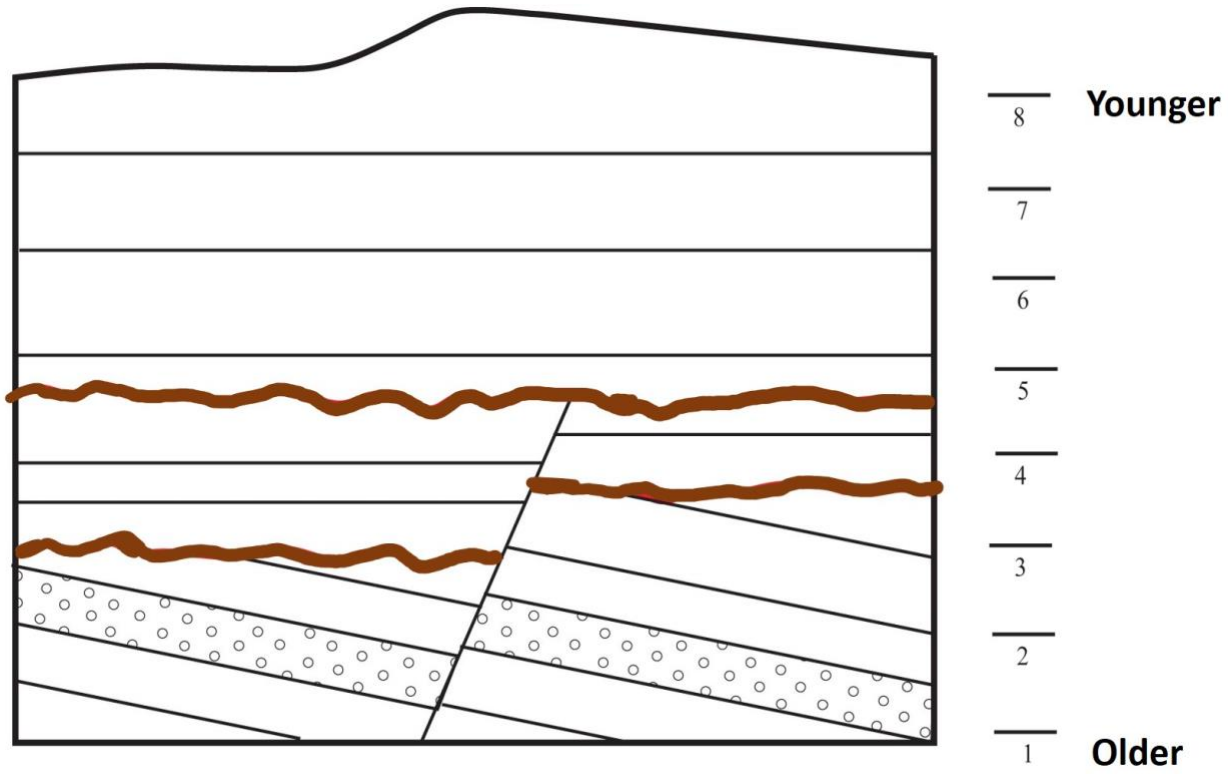

Figure 14.21: Block diagram for Question 9 of Activity 13A.

9. Examine **Figure 14.21**. All the layers in this block diagram are sedimentary rock and the unconformities are the squiggly, brown lines. Consider the unordered, lettered geologic events listed below. Place these events in the correct relative order on the numbered lines to the right of the diagram.

- **a.** Tilting.
- **b.** Uplift and Erosion (Angular Unconformity).
- **c.** Submergence and deposition of sedimentary layers 10-13.
- **d.** Uplift and Erosion to current position.
- **e.** Submergence and Deposition of sedimentary layers 7-9.
- **f.** Uplift and Erosion (Disconformity)
- **g.** Submergence and deposition of sedimentary layers 1-6.
- **h.** Fault.

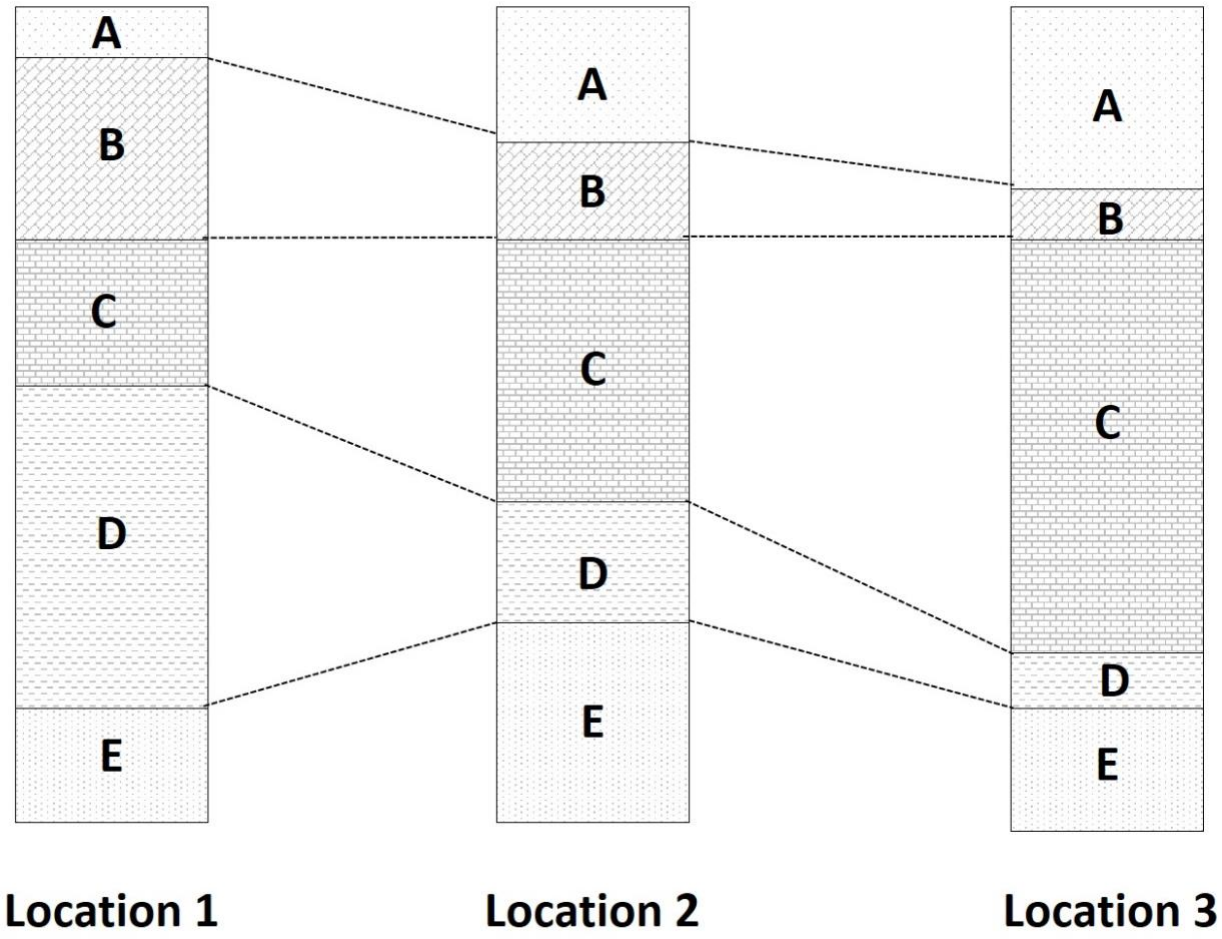

Figure 14.22: Correlation diagram for Question 10 of Activity 13A.

10. Examine **Figure 14.22**. Which Geologic Principle(s) could geologists use to correlate (match) rocks from one locality to another?

Attributions

- Figure 14.18: Derivative of “Block Diagram Questions 1&2” (CC-BY-SA 3.0; Bradley Deline via LibreText) by Chloe Branciforte
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- Figure 14.21: Derivative of “Block Diagram Questions 7,8&9” (CC-BY-SA 3.0; Bradley Deline via LibreText) by Chloe Branciforte
- Figure 14.22: “Correlation of Locations 1-3” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 13B: Relative Dating of Rocks

Figure 14.23: Rainbow Basin Syncline near Barstow, California. Image used for question 1 of Activity 13B.

1. Examine the above image (**Figure 14.23**) from Rainbow Basin, near Barstow, California. Notice the rocks are bent and tilted into a **syncline** (fold). Using the Geologic Principles, relative dating terminology, and your observations of the rock layers, discuss when the folding event likely happened.

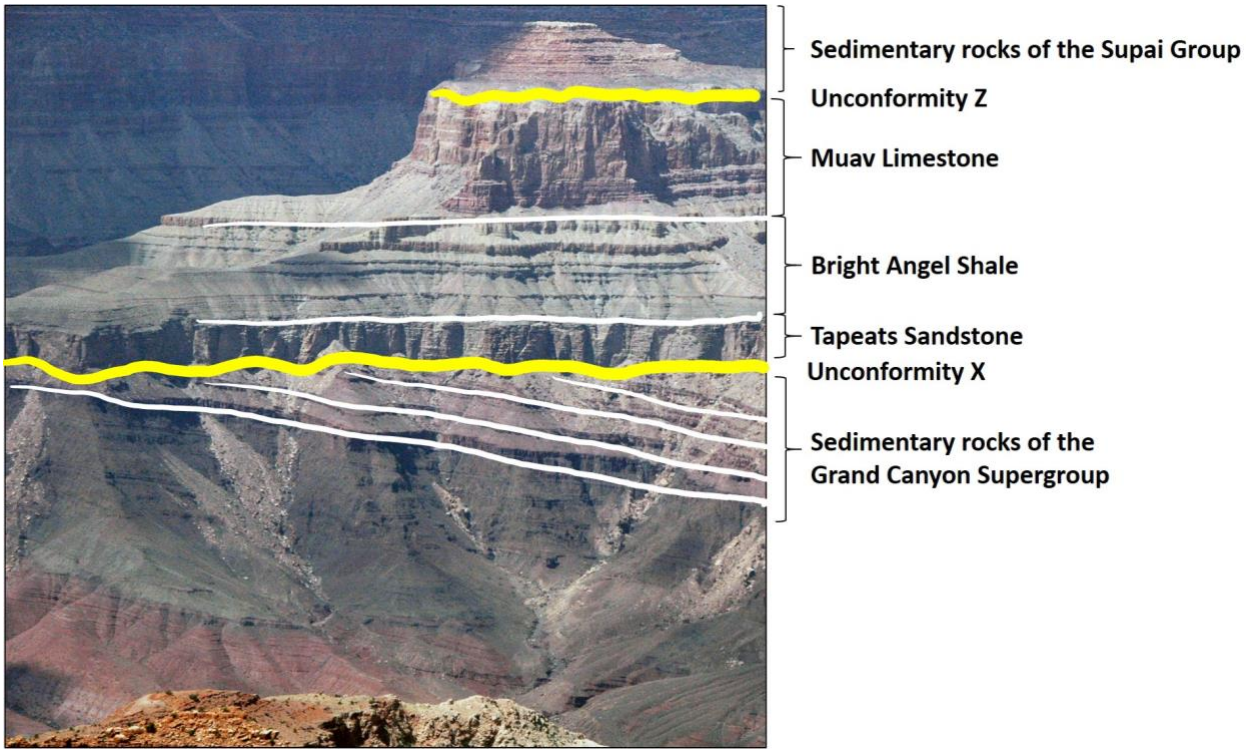


Figure 14.24: Generalized stratigraphy of the Grand Canyon. All rocks are sedimentary. Unconformities are in yellow. Contacts between layers are in white. Image used for question 2 of Activity 13B.

2. The image above (**Figure 14.24**) is from a section of the Grand Canyon. Place the following geologic events in correct order, from oldest to youngest. Support your answers using the Geologic Principles.
- Muav Limestone
- Sedimentary rocks of the Grand Canyon Supergroup
- Tilting event
- Unconformity Z
- Unconformity X
- Tapeats Sandstone
- Sedimentary rocks of the Supai Group
- Bright Angel Shale

Attributions

- Figure 14.23: “Rainbow Basin” (Public Domain; Mark Wilson, Department of Geology, The College of Wooster via Wikipedia)
- Figure 14.24: Derivative of “Grand Canyon” (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte

Activity 13C: T-Charts, Decay Curves, and Half-Lives

Helpful tips to calculate a half-life:

- Draw or insert a T-chart.
- In the T-chart, label the left side with time units (number of half-lives, years, ka, Ma, Ga, etc.)
- Label right side with mass units (percentage, atoms, gram, kilograms, etc.)
- Begin by ALWAYS writing zero in the first spot of the time column.
- In the mass column, begin with the given mass if provided. Recall that this is 100% of the original parent isotope.
    - If the mass is the starting mass, keep dividing the number in the mass column by 2 for each half-life in the left column.
    - If you are given a final mass, record this at the very bottom of the mass column.
        - If the mass given is the final mass, multiply that mass by 2 until the initial time (Time 0) is reached.
        - The final mass amount at the bottom of the mass column equals how much mass is left after radioactive decay has occurred.
- In the time column, add one half-life at a time until you reach the total time given in problem. The number of half-lives elapsed is equal to the number of times you added a half-life in the time column.

1. Calculate the amount of parent isotope remaining for all the given half-lives in this T-chart.

Number of Half-lives	Amount of Parent Isotope Remaining (%)
0	**100**
1	
2	
3	
4	
5	
6	
7	
8	

Table 14.4: T-chart to use in question 1-3 in Activity 13C: T-Charts, Decay Curves and Half-lives.

2. Plot your findings from the T-chart on the graph below.

3. Draw the decay curve by connecting your plotted data points.

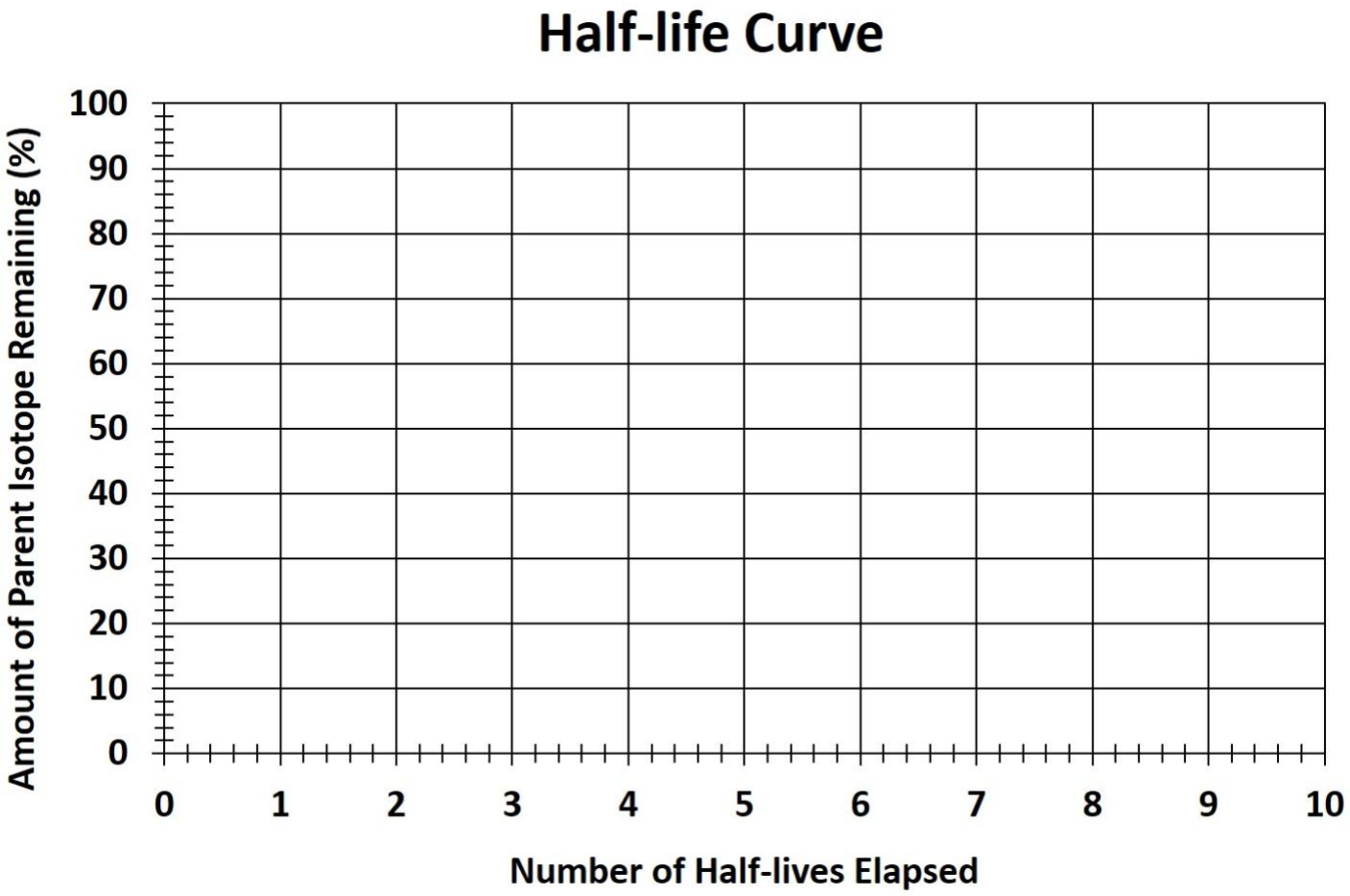


Figure 14.25: Graph to use in question 2-7 in Activity 13C.

Using the above graph (Figure 14.25), answer the following questions.

4. How much of the parent isotope would be remaining after 7 half-lives have passed?

   a. 6.25%
   b. 1.56%
   c. 0.78%
   d. 0.39%

5. If a radiometric element has a half-life of 425 years, how old would a rock be that only had 3.125% of the parent isotope remaining?

- **a.** 2125 years
- **b.** 1700 years
- **c.** 2550 years
- **d.** 3400 years

6. Approximately how much of the parent isotope would be remaining after 3.5 half-lives?

- **a.** 16%
- **b.** 12%
- **c.** 4%
- **d.** 8%

7. Based on your graph above, approximately how many half-lives have passed when only 35% of the parent isotope is remaining?

- **a.** 0.75
- **b.** 1.5
- **c.** 2.1
- **d.** 2.5

Attributions

- Table 14.4: “T-Chart” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 14.25: “Half-life Curve Graph” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 13D: Applying Numeric Dating

1. If a rock begins with 4000 atoms of a radioactive isotope, how many would remain
    a. after one half-life?

    b. after two half-lives?

    c. after three half-lives?

    d. after four half-lives?

2. If an isotope has a half-life of twenty million years, and there is 25% of the isotope remaining in a rock, how old is the rock?

    a. 10 million years
    b. 20 million years
    c. 40 million years
    d. 60 million years

3. A scientist radiometrically dates 3 different rocks using 3 separate decay series. If each rock contains 50% of their measured radioactive element and 50% of its corresponding daughter element, which rock is oldest?

    Rock A is dated using isotope A (half-life = 50 years)
    Rock B is dated using isotope B (half-life = 100 years),
    Rock C is dated using isotope C (half-life = 1000 years).

    a. Rock A
    b. Rock B
    c. Rock C
    d. Impossible to tell

4. An **Archeologist** finds some cotton cloth at a burial site and wants to determine the age of the remains. Which isotopic system should they use?

    a. Carbon-14
    b. Uranium
    c. Potassium-Argon

5. The Archeologist determines that there is 16.7% of the parent isotope remaining in the cloth sample. How old is the burial site? *Hint: you can find the length of the half-life in the reading above.*

- **a.** 13,559 years
- **b.** 14,798 years
- **c.** 16,743 years
- **d.** 1.66 billion years
- **e.** 1.81 billion years
- **f.** 2.05 billion

6. A geologist is trying to date a sequence of sedimentary rocks with abundant fossils and sandstones. Within the sequence is a distinctive clay layer that, under closer inspection, turns out to be fine-grained volcanic ash. Which of the following is the best way to obtain an absolute date for the sequence of rocks?

- **a.** Carbon date the fossils
- **b.** Potassium-Argon date the sands
- **c.** Uranium date the Zircons in the ash
- **d.** Identify the index fossils

7. The geologist determines there is 78.3% of the parent remaining in the sample that they examine. How old is the sequence of rocks? *Hint: you can find the length of the half-life in the reading above.*

- **a.** 187.5 million years
- **b.** 247.8 million years
- **c.** 390.7 million years
- **d.** 2.504 billion years
- **e.** 1.588 billion years
- **f.** 1.202 billion years

Activity 13E: Assembling Geologic Time

In **Figure 14.26**, there are two intrusions that have been numerically dated using K-Ar techniques:

- Intrusion A (dike) has a K-Ar ratio of 87.5% : 12.5%.
- Intrusion B (granite) has a K-Ar ratio of 75% : 25%.

1. What can we say about the age of layer "F" in both numerical and geologic terms?

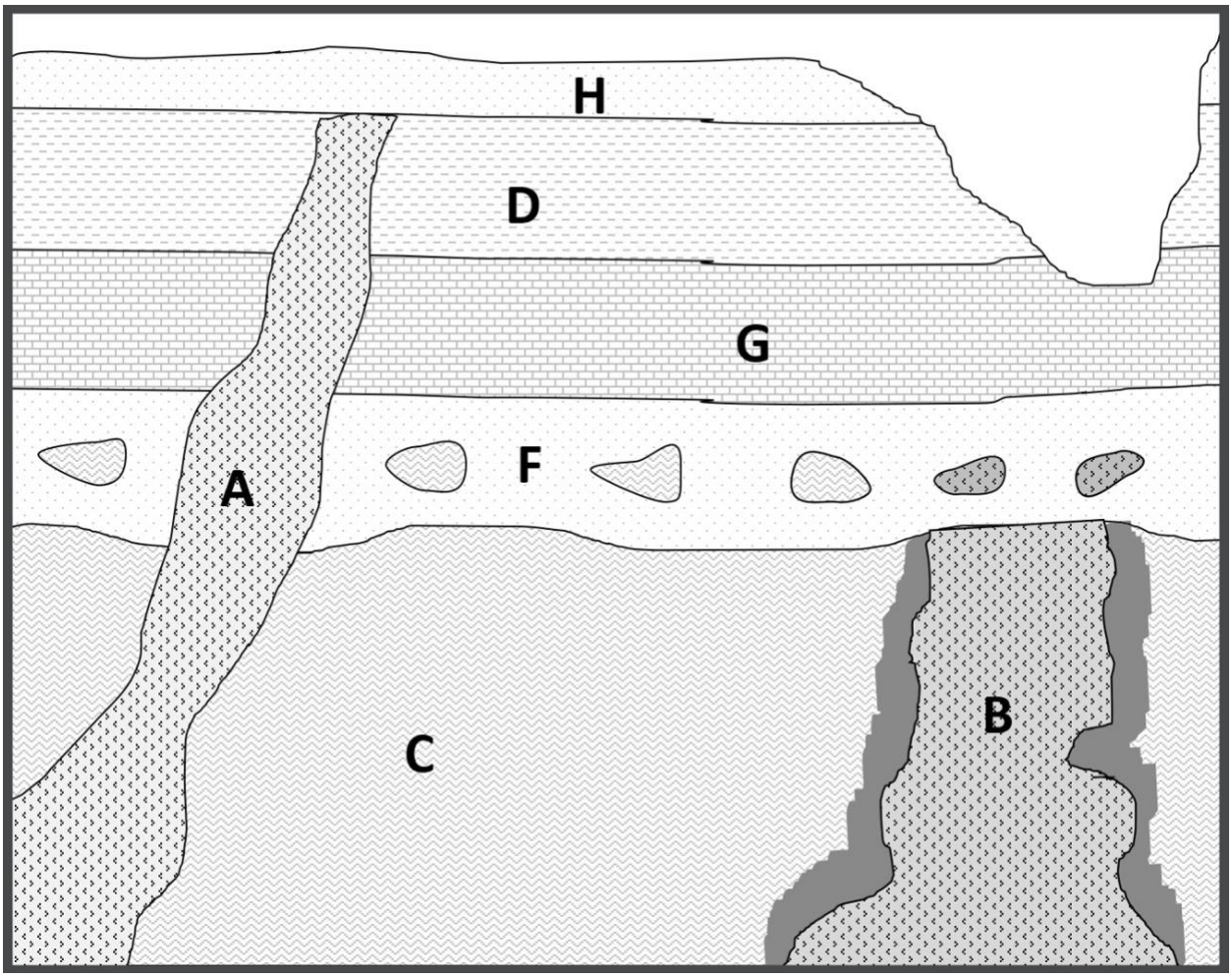


Figure 14.26: Illustration to use in question 1-2 in Activity 13E.

Attributions

- Figure 14.26: “Assembling Geologic Time” (CC-BY 4.0; Chloe Branciforte, own work)

Chapter 15: Geologic Structures

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Understand the different types of stress that rocks undergo, and how rocks respond to stress.
- ✔ Demonstrate an understanding of the concepts of strike and dip.
- ✔ Recognize the different types of folds and faults, and the forces that create them.
- ✔ Use block diagrams to interpret geologic features.

Thumbnail for Chapter 15:

Thumbnail: "Faults, Volcanic Glass, and Tuff" (CC-BY-SA 2.0; Penny Higgins via Flickr)

What Is Crustal Deformation?

The Earth is an active planet shaped by dynamic forces. Such forces can build mountains or crumple and break rocks. As rocks respond to these forces (stress), they undergo **deformation**, which results in changes in shape, placement, and/or volume of the rocks. The resulting features (folds and faults) are termed **geologic structures**. Deformation can produce dramatic and beautiful scenery, as evidenced in **Figure 15.1**, which shows the deformation of originally flat (horizontal) rock layers.

Figure 15.1: Impressive complex folding strata in the Himalayan mountain, Jammu & Kashmir, India.

A person who studies crustal deformation is referred to as a structural geologist. A structural geologist is a geoscientist that studies the bends and breaks of rocks and the conditions under which they form. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research. Other employers consist of museums, state and federal geological surveys, and exploration and mining companies. Becoming a structural geologist requires a college degree and typically postgraduate work. If this is of interest to you, talk to your geology instructor for advice. We recommend completing as many math and science

courses as possible. Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large rock collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 15.1: “Folding in the Himalaya” (CC-BY-NC-SA 3.0; Prakasam Muthus, distributed by imaggeo.egu.eu)

What Is Stress and Strain?

Rocks change as they undergo **stress**, which is just a force applied to a given area. Since stress is a function of area, changing the area to which stress is applied makes a difference. For example, imagine a single steel nail and a bed made entirely of those same nails. If someone were to lay down on a single nail, the stress becomes concentrated at the point, and they would surely hurt themselves. However, lay down on the bed of nails, and the stress becomes distributed and spread out producing a much safer outcome. In geology, there are three main types of stress (**Figure 15.2** and **Table 15.1**):

- **Compressional forces** operate when rocks are pushed together. Typically, rocks can withstand compressional stress better than tensional stress.
- **Tensional (extensional) forces** operate when rocks pull away from each other.
- **Shear forces** are created when rocks move horizontally past each other in opposite directions.

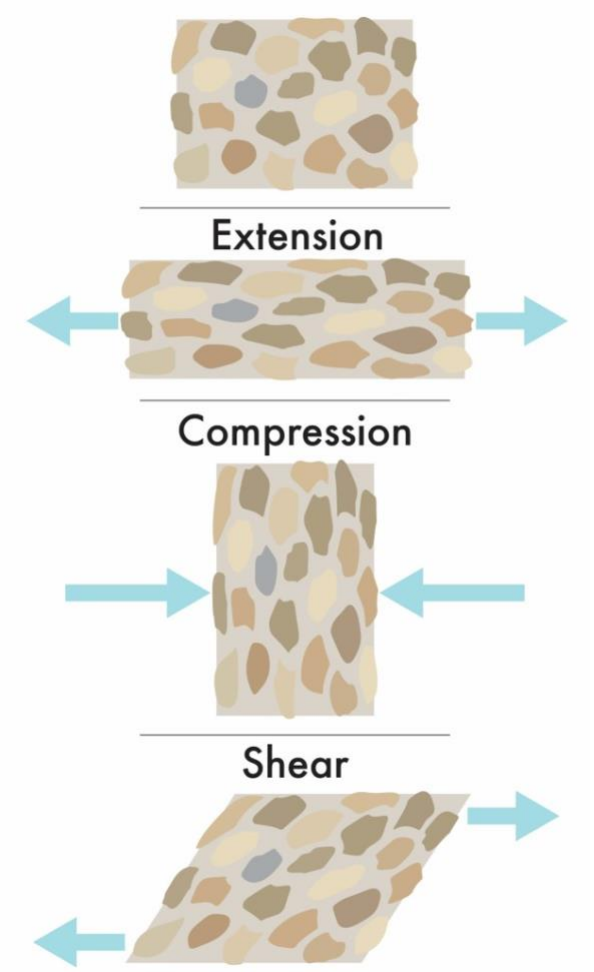


Figure 15.2: *Top*, a block of rock. *Top middle*, the block of rock has undergone extensional (tensional) stress and has elongated and thinned. *Bottom middle*, the original block has undergone compressional stress and has shortened and thickened. *Bottom*, the original block has undergone shear stresses which resulted in each side of the block moving in opposite directions.

In response to these stresses, rocks may undergo three different types of strain:

- **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 (or plastic deformation)** is irreversible. A rock that has undergone ductile strain will remain deformed even if the stress stops. Rocks that undergo ductile deformation typically result in **folding**.
- **Fracture (or brittle deformation)** is also irreversible. A rock that has fractured or ruptured has abruptly broken into distinct pieces. If the pieces are offset, shifted in

opposite directions from each other, the fracture is referred to as a **fault**.

Type of Stress	Crustal Response	Geologic Structures	Associated Plate Boundary
Compression	Shortening & thickening	Reverse faults Folding	Convergent
Tension (extension)	Elongation (stretching) & thinning	Normal faults	Divergent
Shear	Tearing	Strike-slip faults	Transform

Table 15.1: The three stress types.

The resulting deformation depends on many factors, including the type of stress, the type of rock, the depth of the rock (pressure and temperature), and the length of time the rock endures the stress. Rocks behave very differently at depth than at the surface. Generally, rocks at depth deform in a more plastic manner (folds), and in a more brittle manner near the Earth's surface (faults).

Attributions

- Figure 15.2: “Stress” (CC-BY 4.0; Emily Haddad, own work)
- Table 15.1: “Stress” (CC-BY 4.0; Chloe Branciforte, own work)

The Importance of Block Diagrams and Perspective

To learn many of the concepts associated with structural geology, it is useful to consider the geological perspective (**Figure 15.3**). Typically, geologists will use **block diagrams** to depict structures of the Earth. Note the different ways that you can view a block diagram. If you look at a block from along the side, you are seeing the **cross-section (or profile) view**. If you look at the block from directly above it, you are looking at a **map-view**.

As you examine the rocks and consider how they have changed, it is useful to remember how they were deposited in the first place. Take some time to review the **Geologic Principles**, especially the Principle of Original Horizontality and Principle of Superposition.

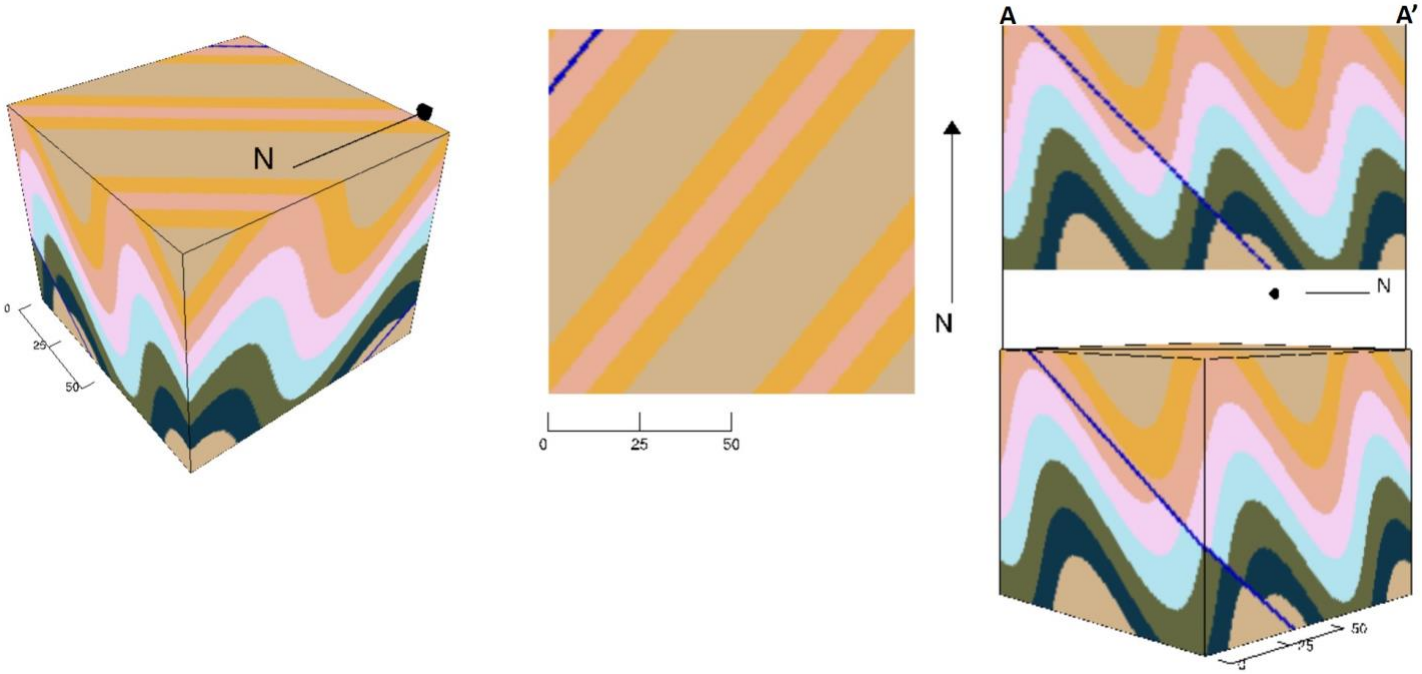


Figure 15.3: Geologic perspectives are important to consider when examining geologic structures.

Attributions

- Figure 15.3: “Geologic Perspectives” (CC-BY 4.0; Chloe Branciforte via Visible Geology)

How Do Geologists Measure Geologic Structures?

Each of the boundaries between rock units represents a **geologic contact**, which is simply the surface between two different rock units. Rock layers are often at an angle, not horizontal, indicating that changes have occurred since deposition. In order to measure and describe layers, geologists apply the concepts of strike and dip.

Strike & Dip

Strike refers to the line formed by the intersection of a horizontal plane and an inclined surface. To determine strike, find where the dipping layer intersects the horizontal surface and draw a line parallel to this line of intersection on the top of the block (i.e. our horizontal surface). In **Figure 15.4**, look at the tilted sedimentary layers. Strike is the line on the horizontal plane created when the dipping green layer intersects the Earth's surface. To better display the horizontal surface, it has been represented by water.

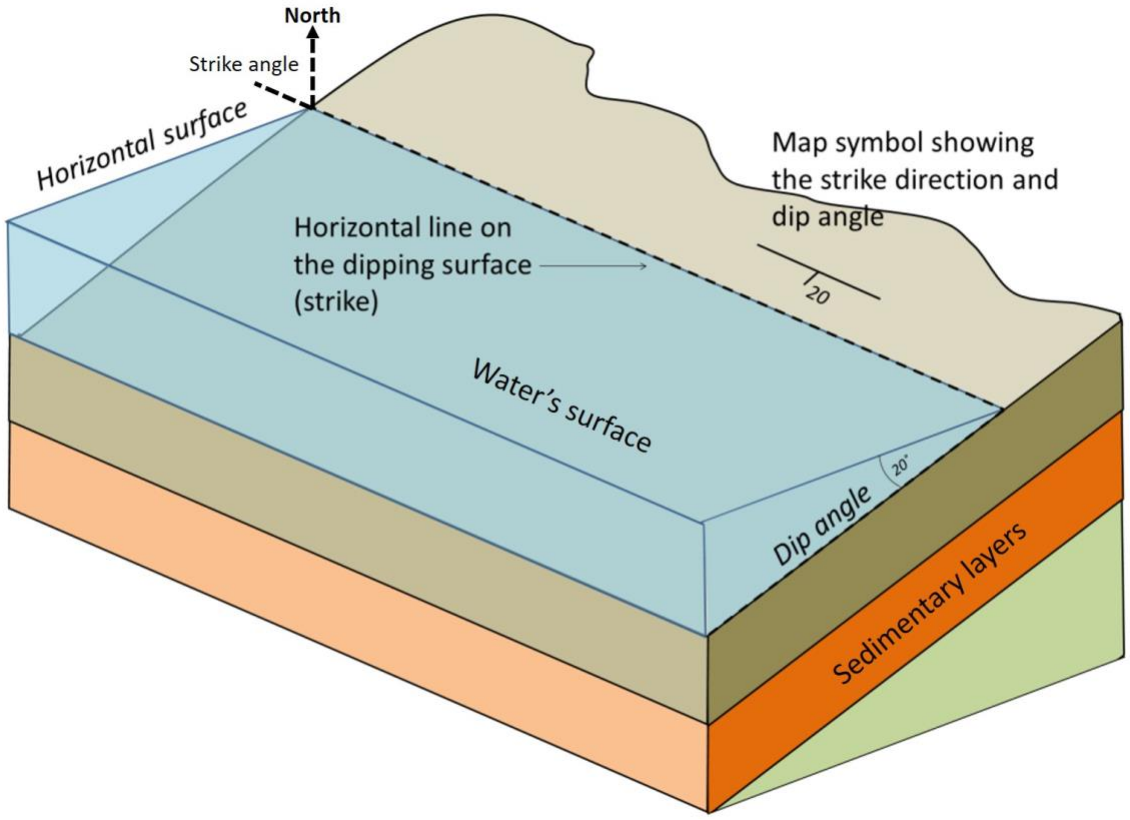


Figure 15.4: A depiction of the strike and dip of some tilted sedimentary beds. The dipping beds are shown partially covered with water so that you can visualize a horizontal line on the rock surface. The notation for expressing strike and dip on a map is also shown.

Dip is the angle between that horizontal plane and the tilted surface (**Figure 15.4**). To determine dip, pretend that there is a drop of water between one bed and the next (for example, along the intersection of the green bed and the orange bed). In which direction would the water roll if it followed that contact? That is the direction of dip, towards the left in this case.

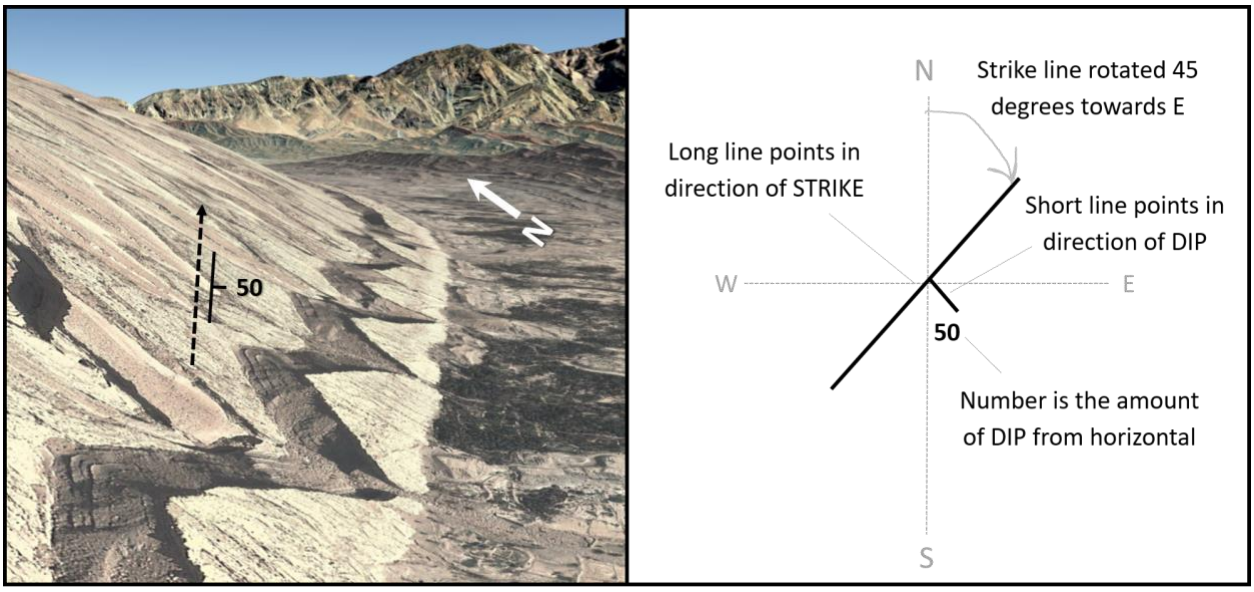


Figure 15.5: *Right*, a strike and dip symbol on tilted sedimentary beds. *Left*, the strike and dip symbol from the diagram on at compass rose to illustrate directional and use of the symbol.

The symbol for strike and dip is illustrated in greater detail on **Figure 15.5**. Note that the dip symbol (shorter line) is perpendicular to the strike symbol; dip degree (number) will vary depending on measurements. You will work more with measuring strike and dip in the next chapter.

When using strike and dip, it is important to remember that with these symbols a geologist can interpret and draw a cross-sectional view from a map-view. Examine **Figure 15.6**, do you notice any patterns between the map and cross-sectional views? Locate the two peach-colored layers in map view and their associated strike and dip symbols. Notice the dips point away from each other. Now, trace a peach-colored layer down to the cross-sectional view; the layers are no longer straight. Instead the layers actually dip away from each other and there is a distinct rainbow pattern. With a protractor measure the angle of dip for the peach-colored layer. You are measuring how many degrees off the horizontal that layer is. In this case the peach-colored layer is 28° off the horizontal, and is what the number associated with the strike and dip symbol signifies. Consider a swiss or jelly roll cake. The cake begins as flat, horizontal layers of cake and filling. Those layers are then deformed by the baker rolling and filling the cake. The final cake

has a distinct rolled shape, which when cut to be served will reveal the curved layers inside.

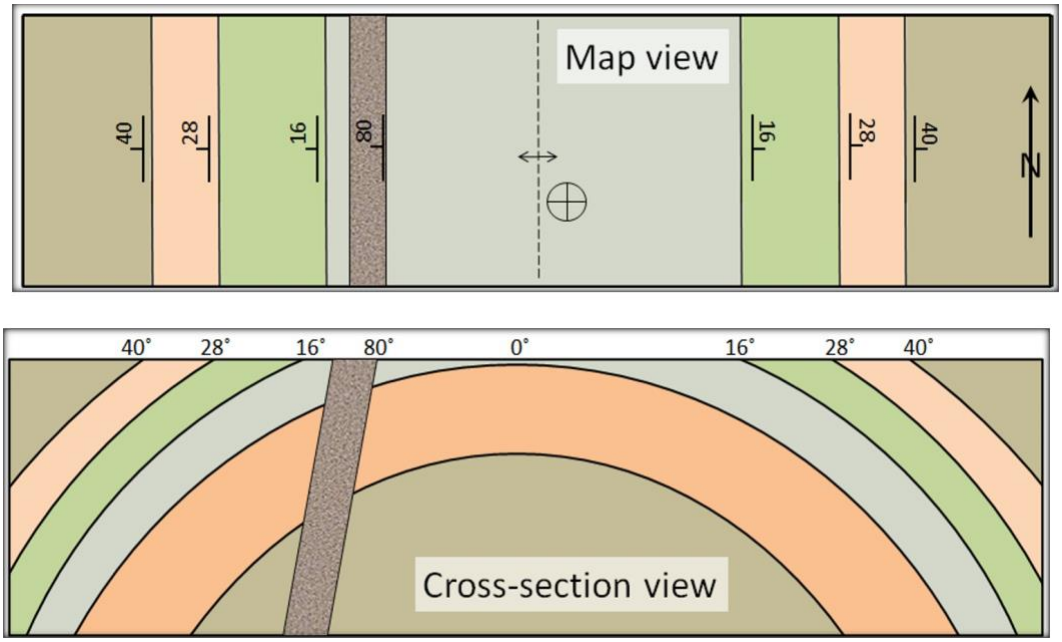


Figure 15.6: A depiction of an anticline and a dike in cross-section and in map view with appropriate symbols.

Useful in map interpretation is the application of the **Rule of V's** to determine dip direction. Recall that due to erosion, sharp-pointed V's are usually in stream valleys, with the stream channel passing through the point of the V, and the V pointing upstream. As a result, when a stream crosses tilted strata, it will cut a V-shape into the rock layers. The point of the V is in the direction of dip. In vertical strata, no V-shapes are made (**Figure 15.7**).

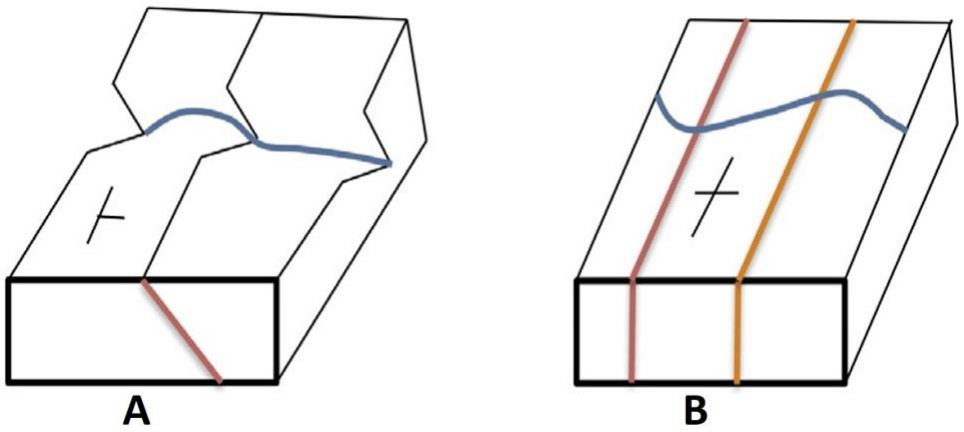


Figure 15.7: In image A, the stream is encountering tilted strata, which results in a V shape that points towards the dip direction (in this case, to the right). In image B, the strata are vertical, so the stream cannot create a V shape.

Attributions

- Figure 15.4: Derivative of “Geologic Perspectives” (CC-BY 4.0; Steven Earle via OpenText) by Chloe Branciforte
- Figure 15.5: “Strike and Dip” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)
- Figure 15.6: Derivative of “Antiform” (CC-BY 4.0; Steve Earle via OpenText) by Chloe Branciforte
- Figure 15.7: Derivative of “Stream and Tilted vs. Horizontal Layers” (CC-BY-SA 3.0; Randa Harris via LibreText) by Chloe Branciforte

Geologic Structures: Folds

Folds are geologic structures created by **ductile (plastic) deformation** of the Earth's crust. To understand how folds are generated, take a piece of paper and hold it up with a hand on each end. Apply compressional forces (push the ends towards each other). You have just created a fold (bent rock layers). Depending on how your paper moved, you created one of the main fold types!

Simple Folds

Simple folds have distinct regions or anatomy. For example, a plane can be drawn through the **fold axis (or hinge)** of a fold and is called the **axial plane** of the fold. The sloping beds on either side of an axial plane are **limbs** (**Figure 15.8**). An anticline or syncline is described as **symmetrical** if the angles between each of limbs and the axial plane are generally similar, and **asymmetrical** if they are not.

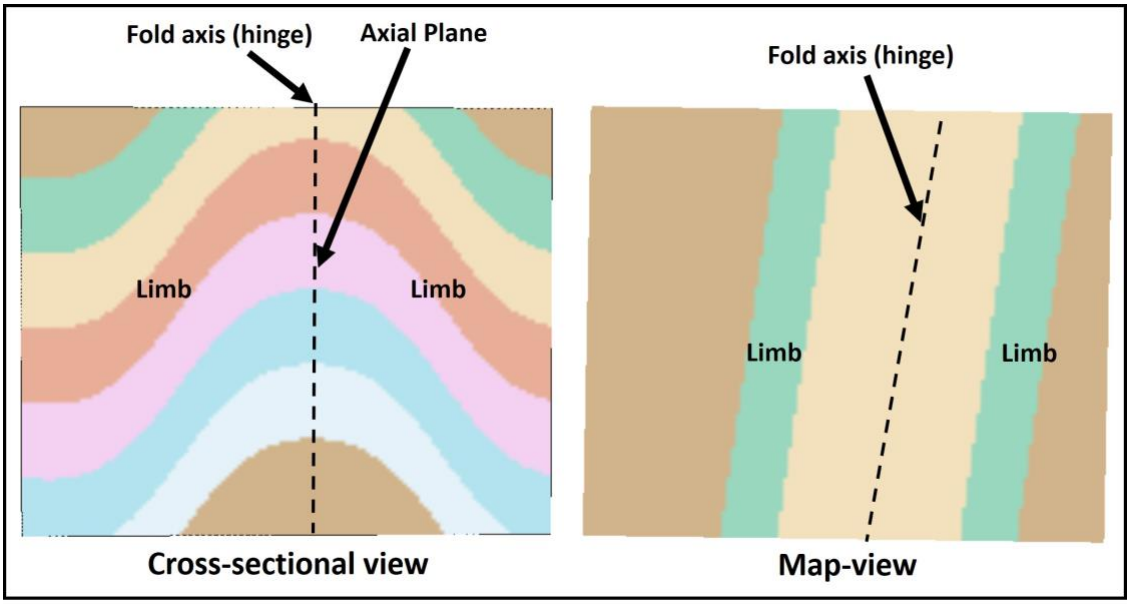


Figure 15.8: The basic anatomy of a simple fold.

Anticlines

An **anticline** has layers which dip away from the hinge of the fold, and in cross-section resembles a capital letter A, rainbow, or arch (**Table 15.2**). In addition to the distinct cross-sectional shape, rocks along the hinge tend to be older, particularly after erosion. This can be determined by using the **Principle of Superposition**. Examine **Figure 15.9**. Mentally flatten the cross-section, so that layers O, S and D are flat and horizontal again. Where does layer O go? It

is located at the bottom, which according to superposition, means it is the older layer. In this instance we also have geologic ages (Devonian, Silurian, and Ordovician), but these periods are only helpful if we know their order or can look up a geologic time scale.

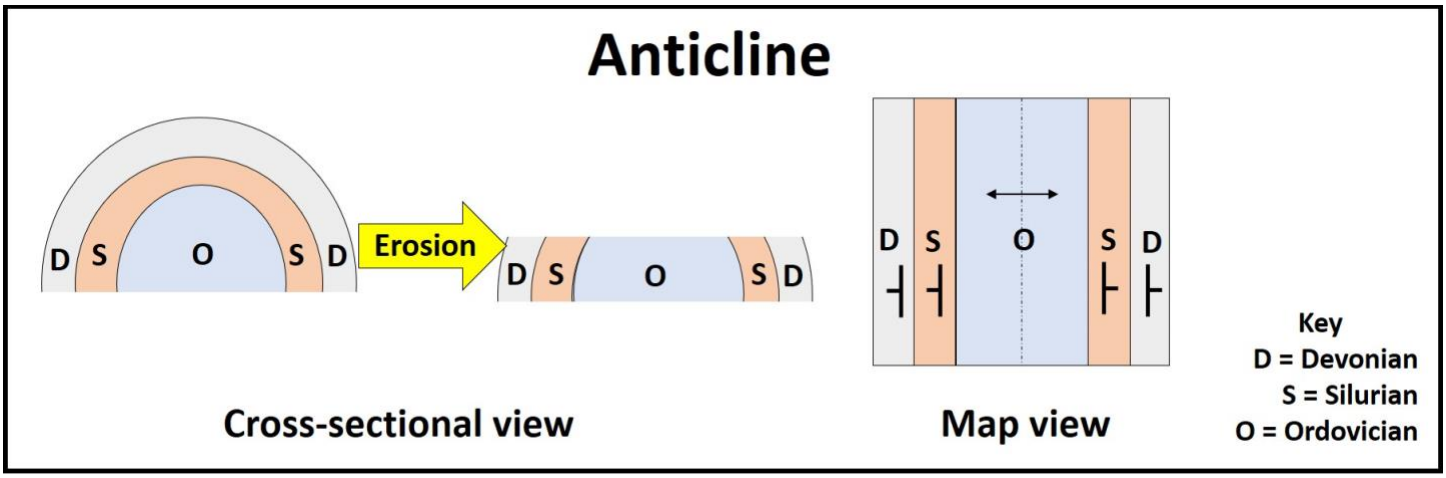


Figure 15.9: An anticline in cross-sectional and map view.

Synclines

A [syncline] has layers which dip towards the hinge of the fold, and in cross-section represents a capital letter U, smile, or sink (**Table 15.2**). In addition to the distinct cross-sectional shape, rocks along the hinge tend to be younger, even after erosion (**Figure 15.10**). Much like above, this can again be determined by using the [Principle of Superposition].

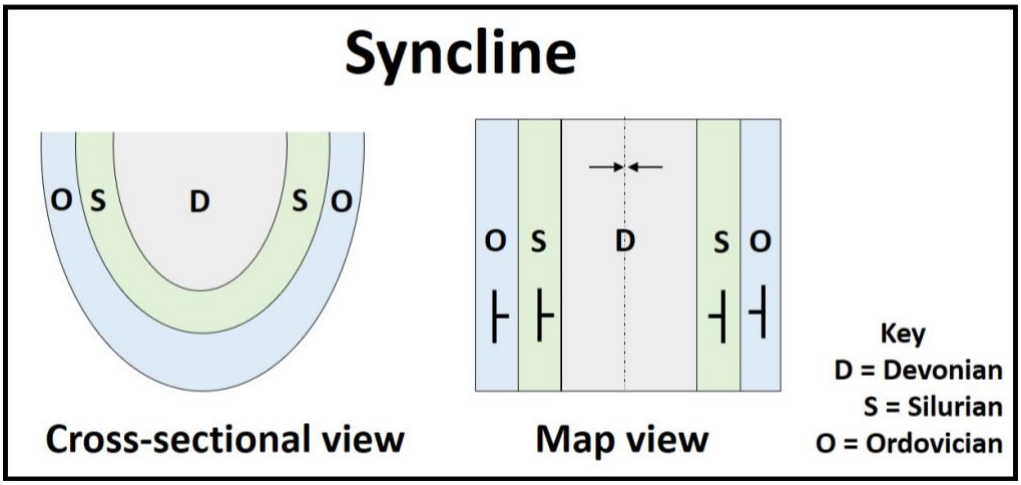


Figure 15.10: A syncline in cross-sectional and map view.

It is important to note that anticlines do not always represent mountains or high areas and synclines do not always represent basins or low areas. They are simply folded rock layers, and do not necessarily indicate topographic high and low points. Notice in both simple folds, the

cross-section looks much different from the map view. In map view, rather than seeing folds, you encounter beds that, after erosion, will be organized as a parallel striped pattern (**Figures 15.9, right** and **15.10, right**). To help determine the simple fold type, it will be helpful to interpret the strike and dip of the beds, age of the rock along the hinge, or any general symbology present.

Simple Folds	Cross-sectional shape	Direction of dip of layers	Age of beds along axis or center
Anticline	A-shape or rainbow	Away from axis	Older
Syncline	U or V-shape or smile	Towards the axis	Younger

Table 15.2: The simple folds.

Plunging Folds

A **plunging fold**, which is essentially a tilted fold that creates a V-shaped pattern on the surface (**Figure 15.11**). In a **plunging anticline**, the oldest strata can be found at the center of the V, and the V points in the direction of the plunge of the fold axis. In a **plunging syncline**, the youngest strata are found at the center of the V, and the V points in the opposite direction of the plunge of the fold axis.

Monoclines

A **monocline** is a simple fold structure, with only one limb folded, and the other remains horizontal. This is similar to the shape of a carpet draped over a stair step (**Figure 15.12**).

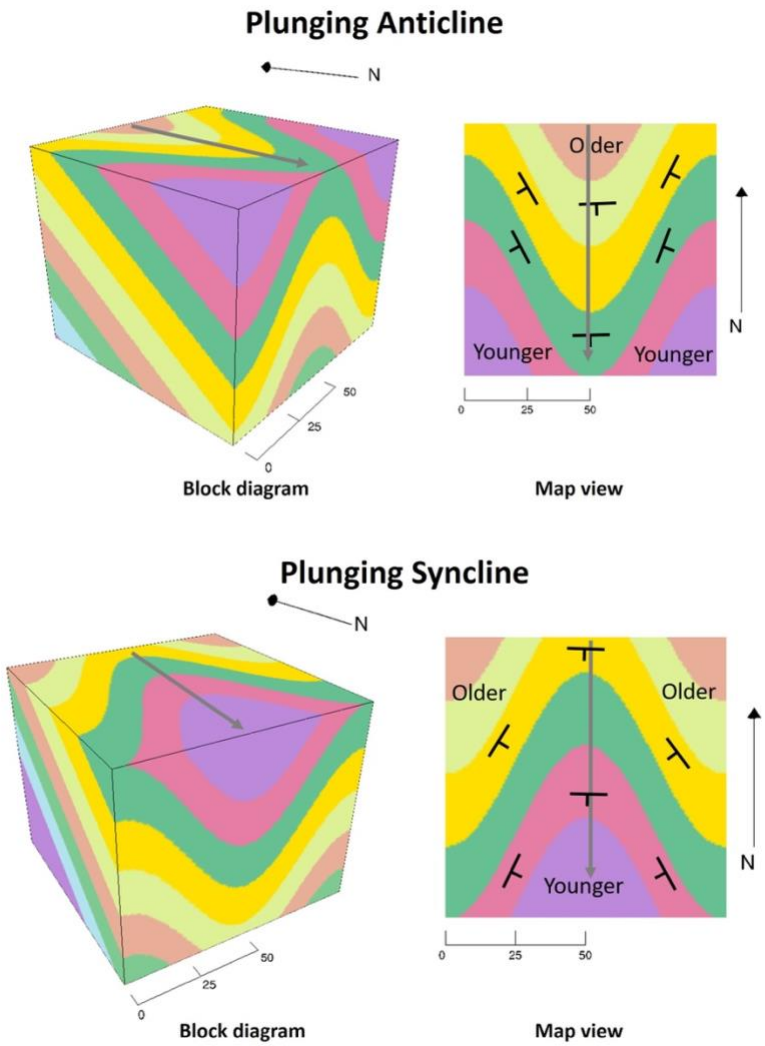


Figure 15.11: A plunging anticline and syncline.

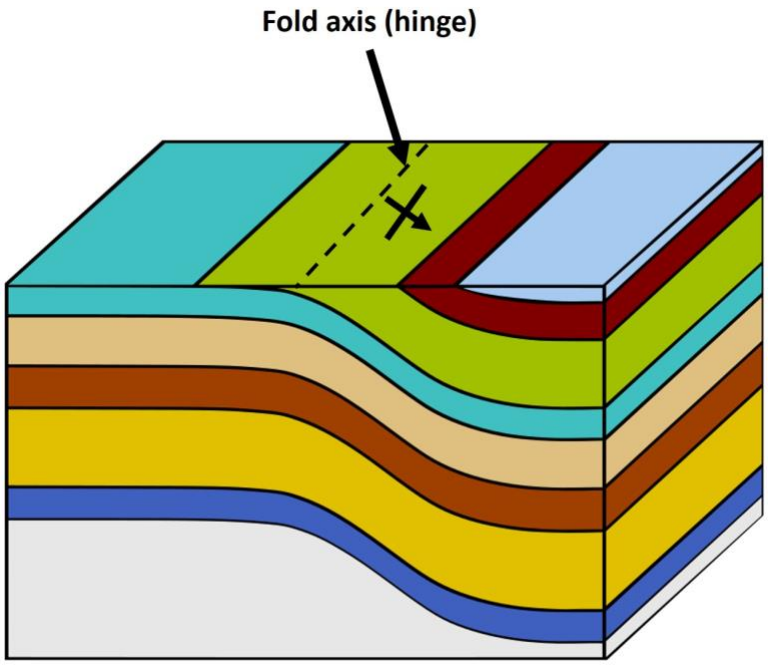


Figure 15.12: Block diagram of a monocline.

Complex Folds

The complex folds include domes and basins, which are basically the circular (or elliptical) equivalent of the simple folds. Both domes and basins can be recognized by their bulls-eye patterned map-view (**Figure 15.13** and **Table 15.3**).

A **dome** has a cross-section similar to an anticline. In a dome, the oldest rocks are exposed at the center, and rocks dip away from this central point. A **basin** has a cross-section, like a syncline. In a basin, the youngest rocks are in the center, and the rocks dip inward towards the center.

Complex Folds	Cross-sectional shape	Direction of dip of layers	Age of beds along axis or center
Dome	A-shape or rainbow (all sides)	Away from center	Older
Basin	U or V-shape or smile (all sides)	Towards the center	Younger

Table 15.3: The complex folds.

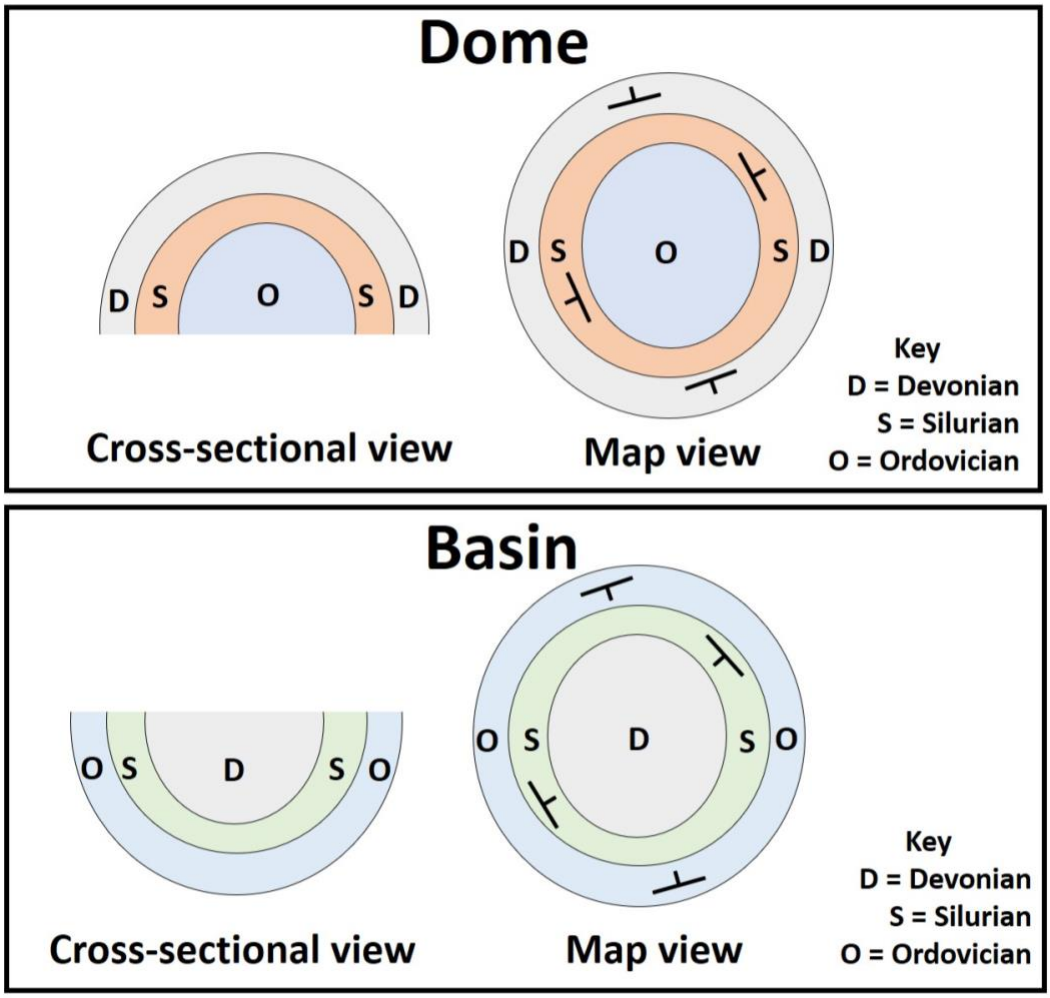


Figure 15.13: The complex folds.

Attributions

- Figure 15.8: “Fold Anatomy” (CC-BY 4.0; Chloe Branciforte via Visible Geology)
- Figure 15.9: “Anticline” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 15.10: “Syncline” (CC-BY 4.0; Chloe Branciforte, own work)
- Table 15.2: “Simple Folds” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 15.11: “Plunging Folds” (CC-BY-SA 4.0; Elizabeth Johnson via VIVA)
- Figure 15.12: “Monocline01” (CC-BY-SA 3.0; Kilom691 via Wikipedia)
- Table 15.3: “Complex Folds” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 15.13: “Complex Folds” (CC-BY 4.0; Chloe Branciforte, own work)

Geologic Structures: Faults

As rocks undergo **brittle deformation**, they may produce cracks in the rocks. If no appreciable displacement has occurred along these cracks, they are called **joints**. If appreciable displacement does occur, they are referred to as **faults**.

Dip-Slip Faults

We will first examine **dip-slip faults**, in which movement along the fault is vertical, either up or down. The two masses of rock that are cut by a fault are termed the **fault blocks**. The type of fault is determined by the direction that the fault blocks have moved. Fault block movement is described based on the movement of the **hanging wall**: the fault block located above the fault plane (**Figure 15.14**). The other fault block, located beneath the fault plane, is called the **foot wall** (**Figure 15.14**). These terms come from the idea that if a miner were climbing along the fault plane, they would hang their lantern above their head, along the hanging wall. Alternately, you can draw a stick figure straight up and down across the fault plane. Its head will be on the hanging wall and its feet will be on the foot wall.

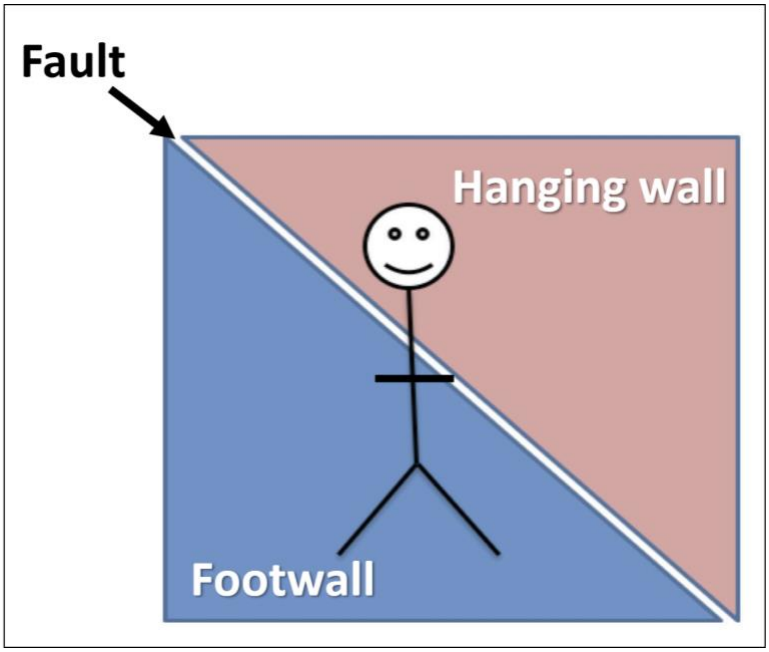


Figure 15.14: A cross-section of a dip-slip fault.

When extensional stresses are applied to the fault blocks, the hanging wall will move down, creating what is called a **normal fault**. An easy way to remember this is the phrase "It's normal to fall down". Extensional stresses cause the crust to become stretched (elongated) and thinned out (**Figure 15.15** and **Table 15.4**). These faults are common, but not exclusive to, rifts and divergent boundaries. Check out this **USGS normal fault video** to visualize the motion further.

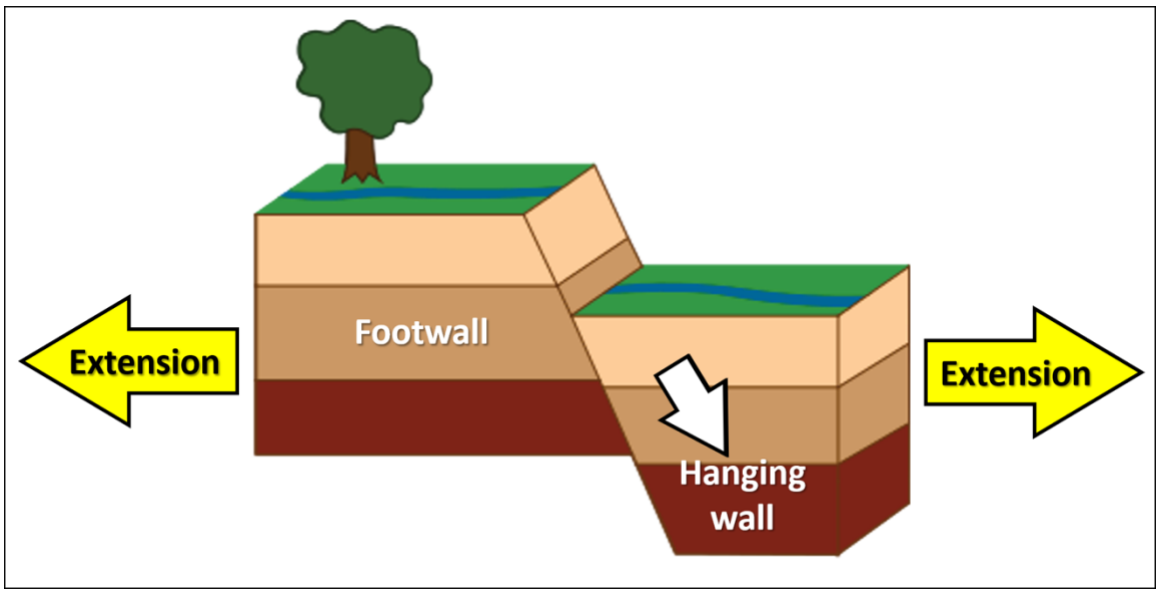


Figure 15.15: A normal fault.

Tensional forces acting over a region can produce normal faults that result in landforms known as horst and grabens. The **graben** is the crustal block that down drops, and is surrounded by two **horsts**, the relatively uplifted crustal blocks (**Figure 15.16**). This terrain is typical of the **Basin and Range of the western United States**. Check out this **USGS horst and graben video** to visualize the motion further.

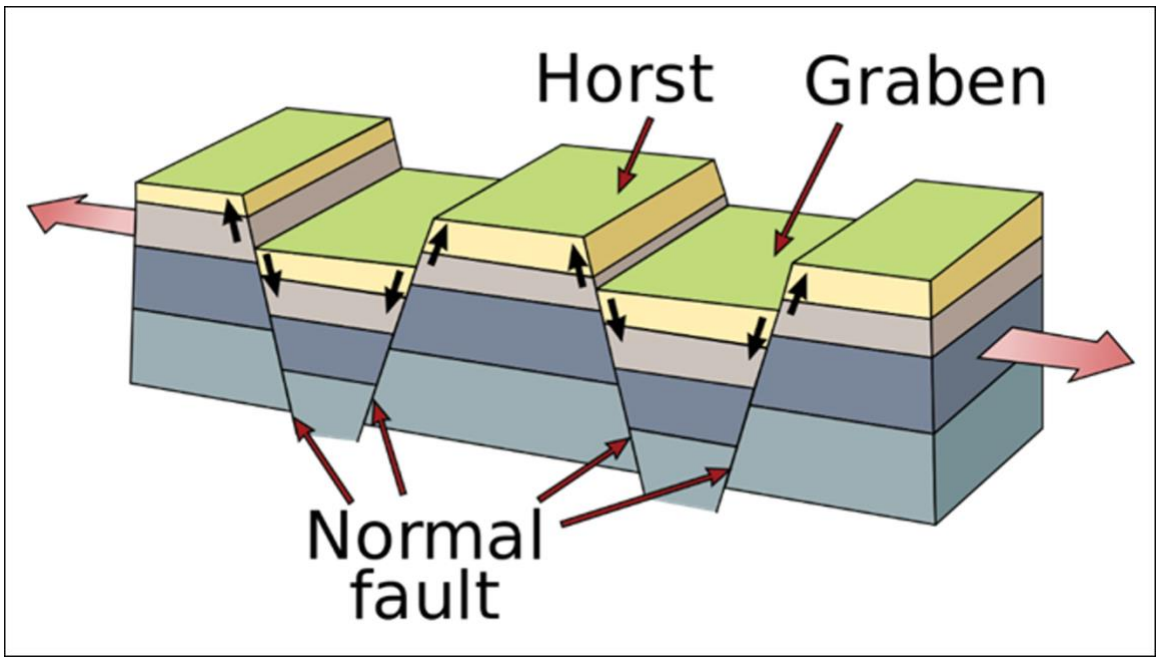


Figure 15.16: An area that has been stretched by tensional forces, resulting in numerous normal faults and horst and graben landforms.

When compressional forces are applied to the fault blocks, the hanging wall will move up, creating a **reverse fault** (**Figure 15.17** and **Table 15.4**). This causes the crust to shorten in the area. A special type of reverse fault is a **thrust fault**, a low angle reverse fault (dip angle of less than 45°) that has a much thinner hanging wall. Check out this **USGS thrust fault video** to visualize the motion of a reverse fault further. These faults are common at, but not exclusive to, convergent boundaries.

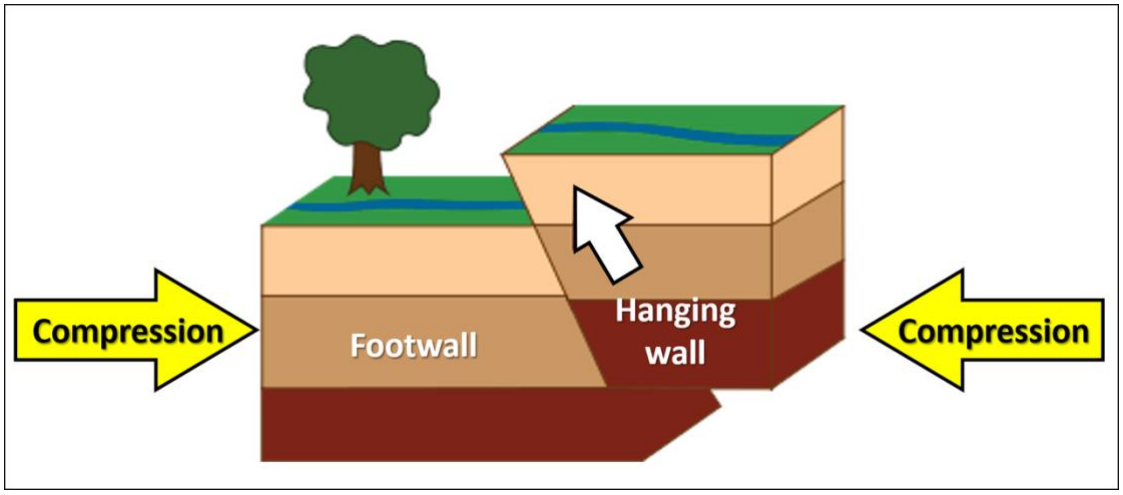


Figure 15.17: A reverse fault.

Strike-Slip Faults

In a **strike-slip fault**, horizontal motion occurs, in the direction of strike (hence the name), with blocks on opposite sides of a fault sliding past each other due to shear forces (**Figure 15.18** and **Table 15.4**). Movement is therefore either to the left or to the right.

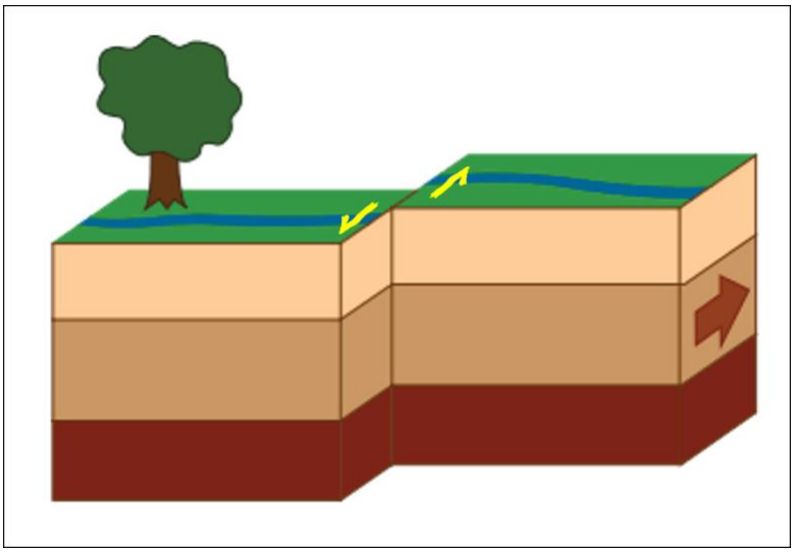


Figure 15.18: A left-lateral strike-slip fault.

The San Andreas Fault here in California is a classic example of a right-lateral strike-slip fault (**Figure 15.19**). To determine the relative sense of motion, an observer would stand along one side of the fault, looking across at the opposite fault block. If that fault block appears to have moved right, it is right-lateral; if it has moved left, it is left-lateral. Check out this **USGS strike-slip fault video** to visualize the motion further.

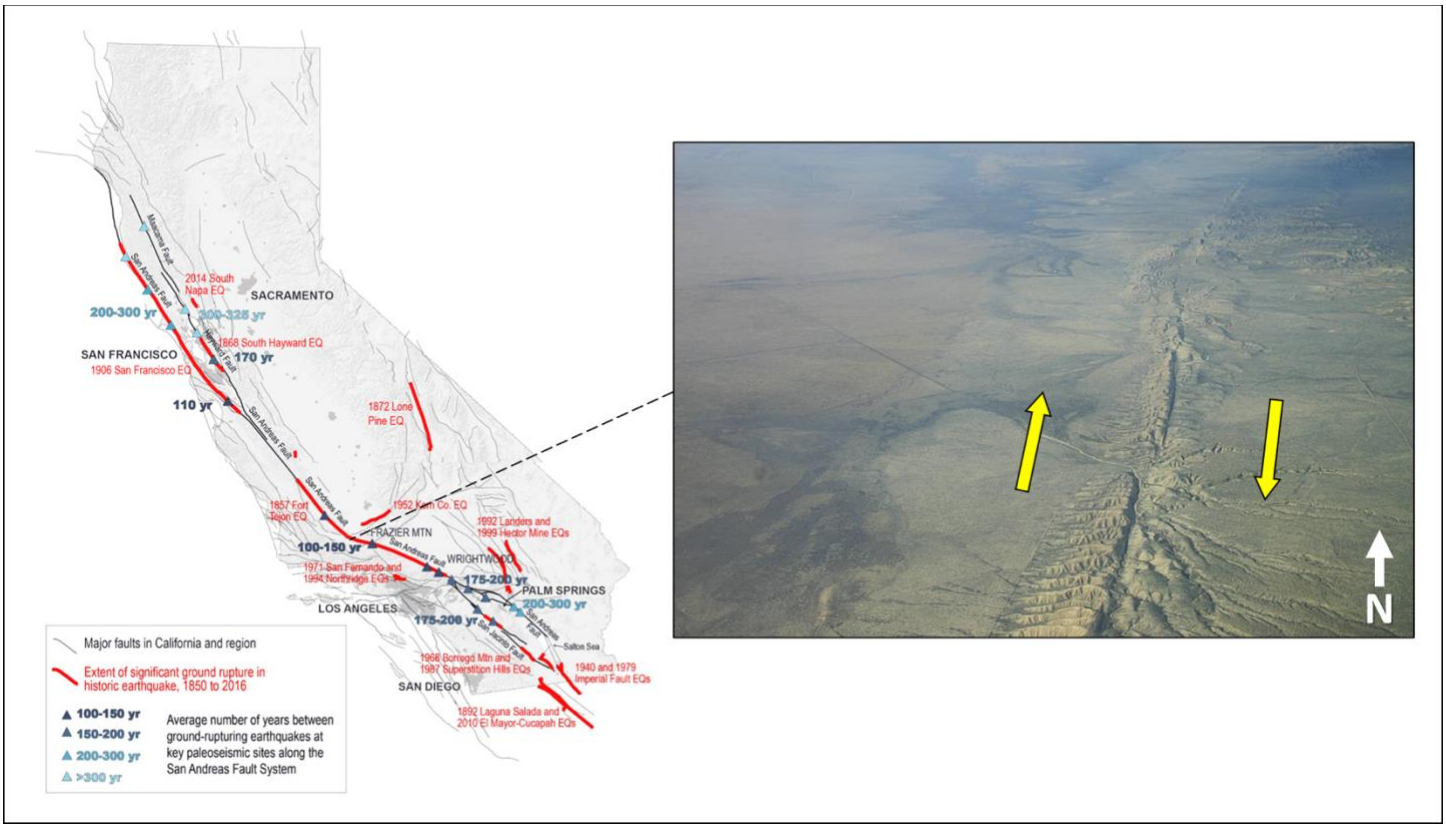


Figure 15.19: *Left*, map of faults in California. *Right*, aerial image of the San Andreas Fault at the Carrizo Plain.

Fault type	Type of Stress	Direction of block movement	Resulting strain	Associated plate boundary type
Normal	Extensional	Vertical; HW moves down	Stretching & thinning	Divergent & rifting
Reverse	Compressional	Vertical; HW moves up	Shortening & thickening	Convergent
Strike-slip	Shear	Horizontal; left or right	Tearing	Transform

Table 15.4: The fault types.

Attributions

- Figure 15.14: Derivative of “Dip-Slip Faults” (CC-BY-SA 3.0; Randa Harris via LibreText) by Chloe Branciforte
- Figure 15.15: Derivative of “Normal Fault” (Public Domain; USGS) by Chloe Branciforte
- Figure 15.16: “Fault-Horst-Graben” (Public Domain; Gregors via Wikimedia Commons)
- Figure 15.17: Derivative of “Thrust Fault” (Public Domain; USGS) by Chloe Branciforte
- Figure 15.18: Derivative of “Strike-slip Fault” (Public Domain; USGS) by Chloe Branciforte
- Figure 15.19: Derivative of “San Andreas Fault” (Public Domain; Karen Scharer/USGS, 1 and 2) and “Kluft-Photo-Carrizo-Plain-Nov-2007-Img 0327” (CC-BY 4.0; Ikluft via Wikimedia Commons) by Chloe Branciforte
- Table 15.4: “Fault Types” (CC-BY 4.0; Chloe Branciforte, own work)

Geologic Maps

What Are Geologic Maps and Why Are They Important?

A **geologic map** uses lines, symbols, and colors to illustrate information about the nature and distribution of rock units within an area (**Figure 15.20**). Typically, a geologic map will depict mappable rock or sediment units. A **mappable unit** of rock or sediment is one that a geologist can consistently recognize, trace across a landscape, and describe so that other geologists may recognize and verify its presence and identity. Generally, a mappable unit is a **geologic formation**. These mappable units are shown as different colors or patterns on a base map (usually a **topographic map**), over which information about geologic contacts and strikes and dips are included. Geologists make these maps by making careful field observations at numerous **outcrops** (exposed rocks at the Earth's surface) throughout the mapping area. At each outcrop, geologists record information such as rock type, strike and dip of the rock layers, and relative age data. Geologic maps take practice to understand, since they display three-dimensional features, such as folds, on a two-dimensional surface.

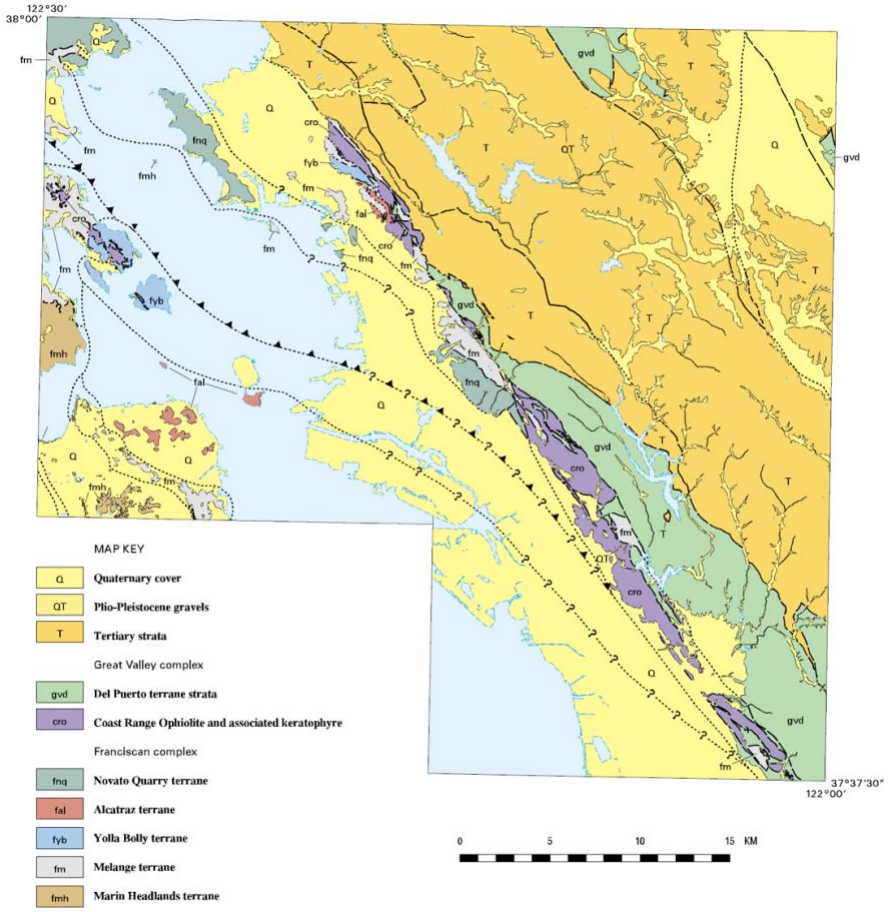


Figure 15.20: Simplified geologic map illustrating Mesozoic terranes in and around the Bay Area.

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, engineering, and hazard assessment. Geologic maps are also vital in finding and developing geological resources, such as sediments, groundwater, fossil fuels, and minerals.

What Are the Essential Components of Geologic Maps?

Most geologic maps have the following features (**Figure 15.21**):

1. The map itself
2. The map legend or key that explains all the symbols on the map
3. Geologic cross-section(s) of the map area. These will be explored further in the next chapter.

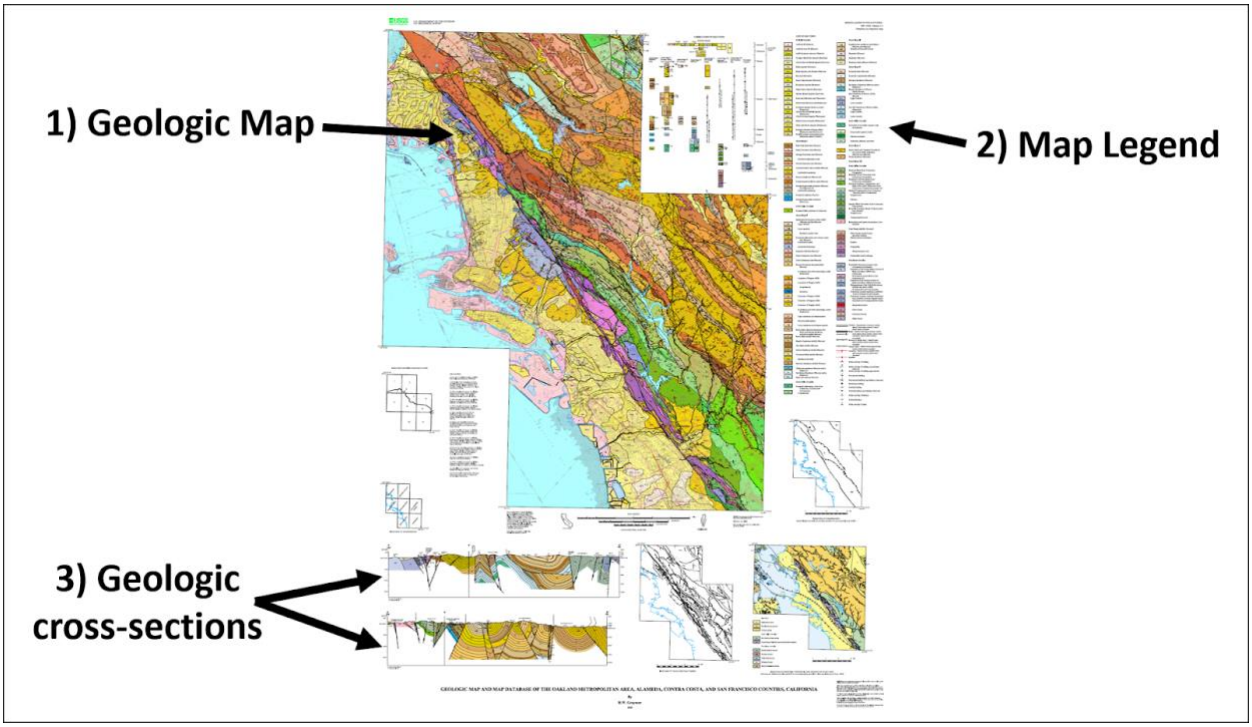


Figure 15.21: 1) Geologic map, 2) legend and 3) cross-sections.

What Is a Geologic Map Legend?

The map legend to a geologic map is usually printed on the same page as the map and follows a customary format (**Figure 15.22**).

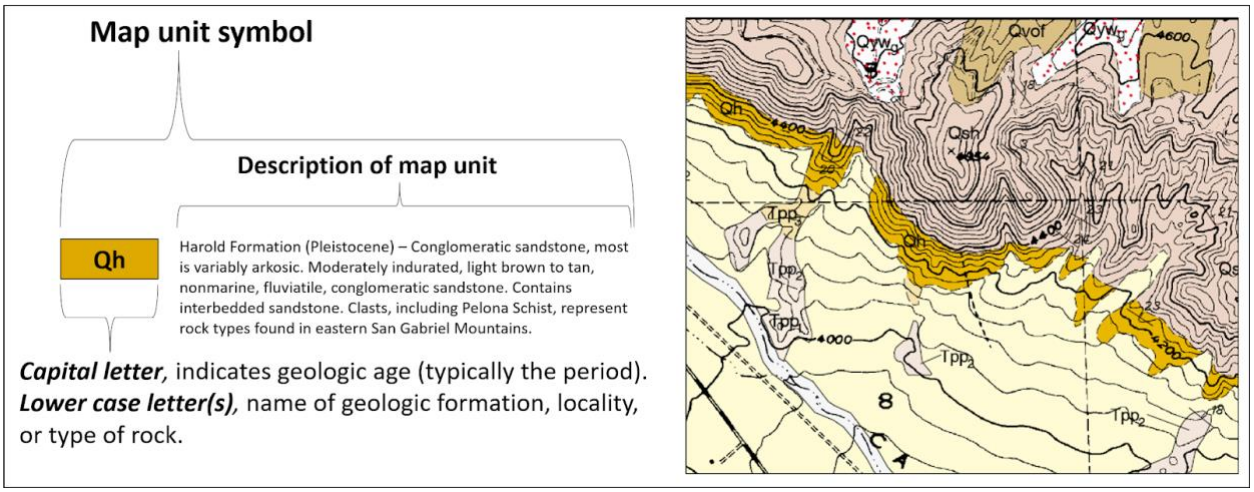


Figure 15.22: General formatting for the legend of a geologic map.

The symbol for each formation, or unit, is shown in a box next to its name with a brief description. The symbols typically follow superposition and are stacked in an age sequence from oldest at the bottom to youngest at the top. This allows the map reader to quickly assess the relative age of each unit. The geologic age (typically the geologic period) is listed for each unit in the key and uses standard symbols (**Table 15.6**). The map legend also contains an explanation of the symbols shown on the map, such as the symbols for different types of faults and folds (**Table 15.5**). The explanations of rock units often follow the map symbol on the map, but for very large maps 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.

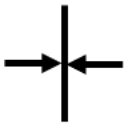
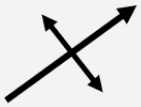
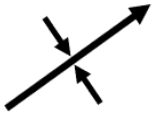
Map Symbol	Symbol Explanation
	Strike & Dip
	Vertical strata
	Horizontal strata
	Anticline axis
	Syncline axis
	Plunging anticline axis
	Plunging syncline axis
	Fault
	Strike-slip fault
	Normal fault
	Reverse fault

Table 15.5: General geologic map symbols.

Relative Age	Geologic Age Symbol	Geologic Time Period
Younger	Q	Quaternary
	T	Tertiary
	K	Cretaceous
	J	Jurassic
	Tr	Triassic
	P	Permian
	IP	Pennsylvanian
	M	Mississippian
	D	Devonian
	S	Silurian
	O	Ordovician
	Є	Cambrian
Older	pЄ	Precambrian

Table 15.6: General geologic age symbols.

A Few General Rules for Interpreting Geologic Maps

- **Folds**
  - **Anticlines** have their oldest beds in the center, and their limbs (sides) dip away from the fold axis or hinge. **Plunging anticlines** plunge towards the closed end (nose) of the V-shaped outcrop belt.
  - **Synclines** have their youngest beds in the center, and their limbs (sides) dip toward the fold axis or hinge. **Plunging synclines** plunge toward the open end of the V-shaped outcrop belt.

- **Streams**
  - They intersect dipping beds of rock, they will cut V shapes in the direction of dip.
  - They cut "V" shapes into horizontal beds and formation contacts that point upstream. The formation contacts are parallel to topographic contour lines, and the stream drainage system developed on horizontal and/or unstratified formations has a dendritic pattern that resembles the branching of a tree.

    - They cut across vertical beds, there will not be a V-shape

- **Faults**
    - Upthrown blocks of faults tend to be eroded more (down to older beds) than downthrown blocks.

- **General**
    - Geologic contacts migrate downdip upon erosion.
    - True dip angles can only be seen in cross-section if the cross-section is perpendicular to the fault or to the strike of the beds.

Attributions

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- Figure 15.21: Derivative of “Geologic Map and Map Database of the Metropolitan Area, Alameda, Contra Costa, and San Francisco Counties, California” (Public Domain; R.W. Gramer/USGS) by Chloe Branciforte
- Figure 15.22: Derivative of “Geologic Map of the Telegraph Peak 7.5’ Quadrangle, San Bernardino County, California” (Public Domain; D.M Morton, M.O Woodburne, and J.H. Foster/USGS) by Chloe Branciforte
- Table 15.5: “Geologic Map Symbols” (CC-BY; Chloe Branciforte, own work)
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Activity 15A: Reading and Interpreting Geologic Map Symbology

1. Why do geologists take strike and dip measurements?

2. What tools are used, in the field & in the lab, to measure strike and dip?

3. Define the following terms:

a. Strike:

b. Dip:

4. Label the 3 parts of the following map symbol:

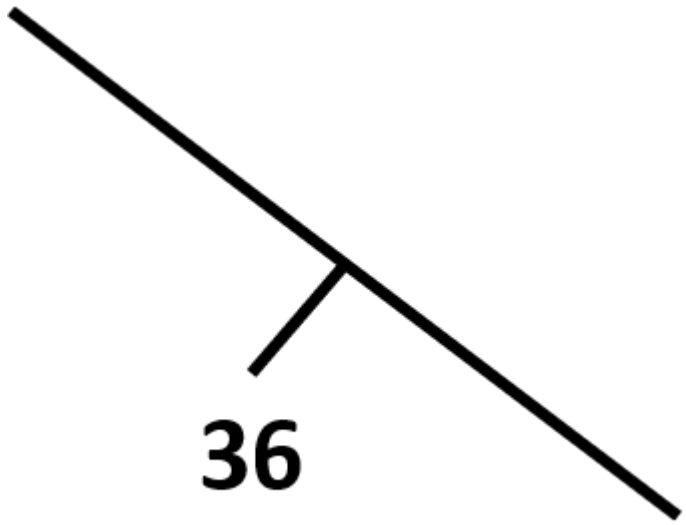


Figure 15.23: Figure for Question 4 in Part 15A.

5. Interpret each strike & dip symbol in **Figure 15.24**. Assume north is to the top of the page. Use the format: ***strike, dip angle, dip direction.*** See the example for how to write this successfully.

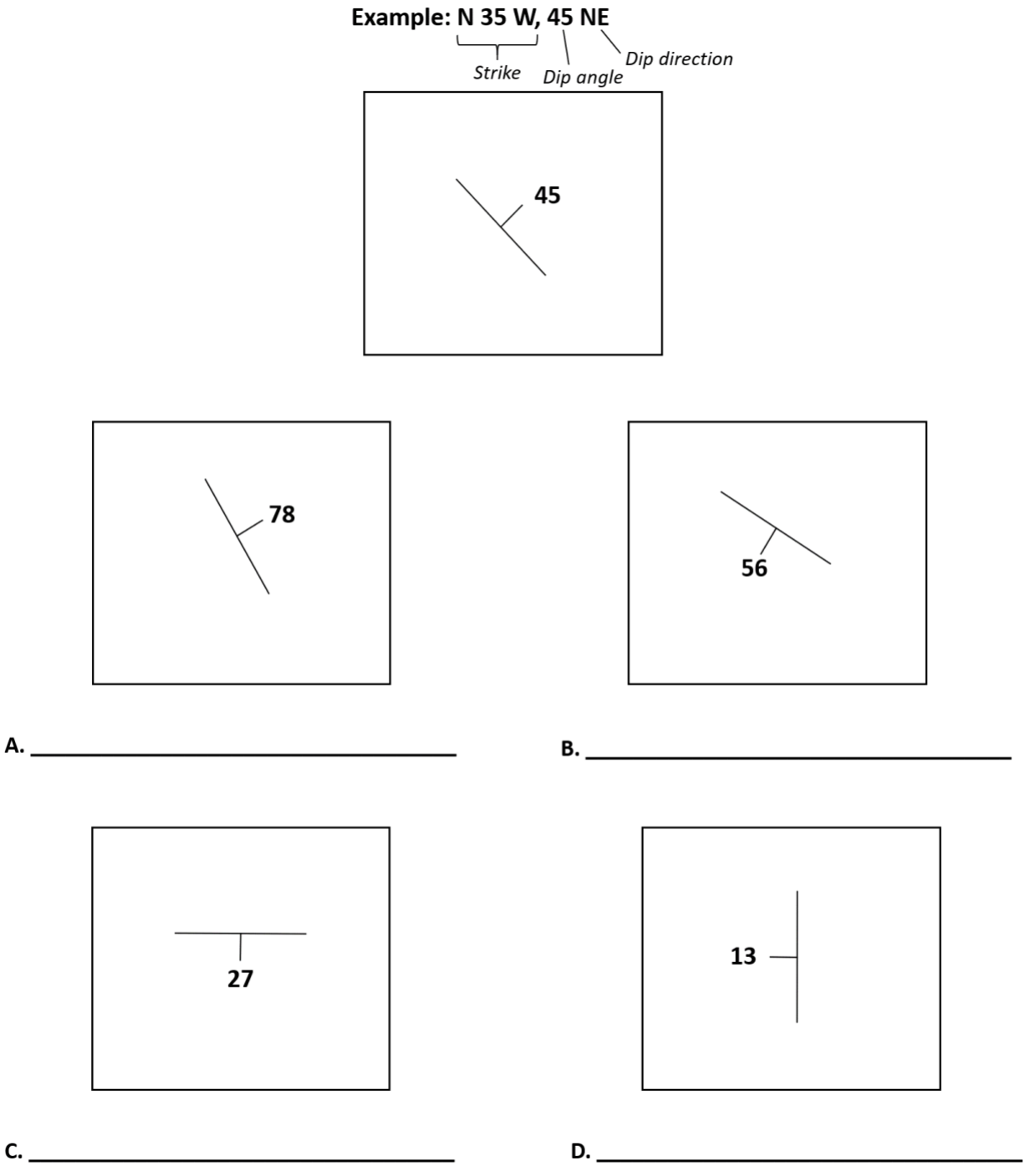
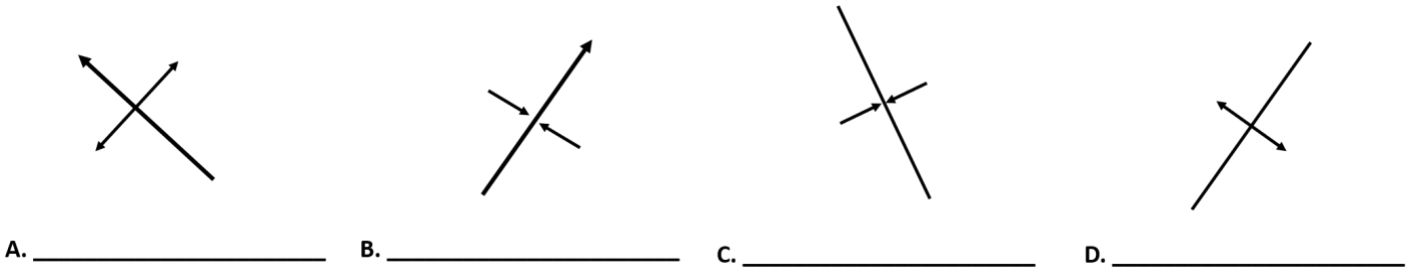


Figure 15.24: Figure for Question 5 in Part 15A.

6. Name the geologic structure indicated by each of the following map symbols:



A. _____ B. _____ C. _____ D. _____

Figure 15.25: Figure for Question 6 in Part 15A.

Attributions

- Figure 15.23: “Strike and Dip Practice” (CC-BY; Chloe Branciforte, own work)
- Figure 15.24: “Strike and Dip Practice” (CC-BY; Chloe Branciforte, own work)
- Figure 15.25: “Fold Symbols” (CC-BY; Chloe Branciforte, own work)

Activity 15B: Reading and Interpreting Block Diagrams

1. After erosion, where would you find the older rock layers in each of the following structures?
   - **a.** An anticline:
   - **b.** A syncline:
   - **c.** A dome:
   - **d.** A basin:

2. Draw the appropriate map symbols, including strike and dip, for the fold on the map view below.

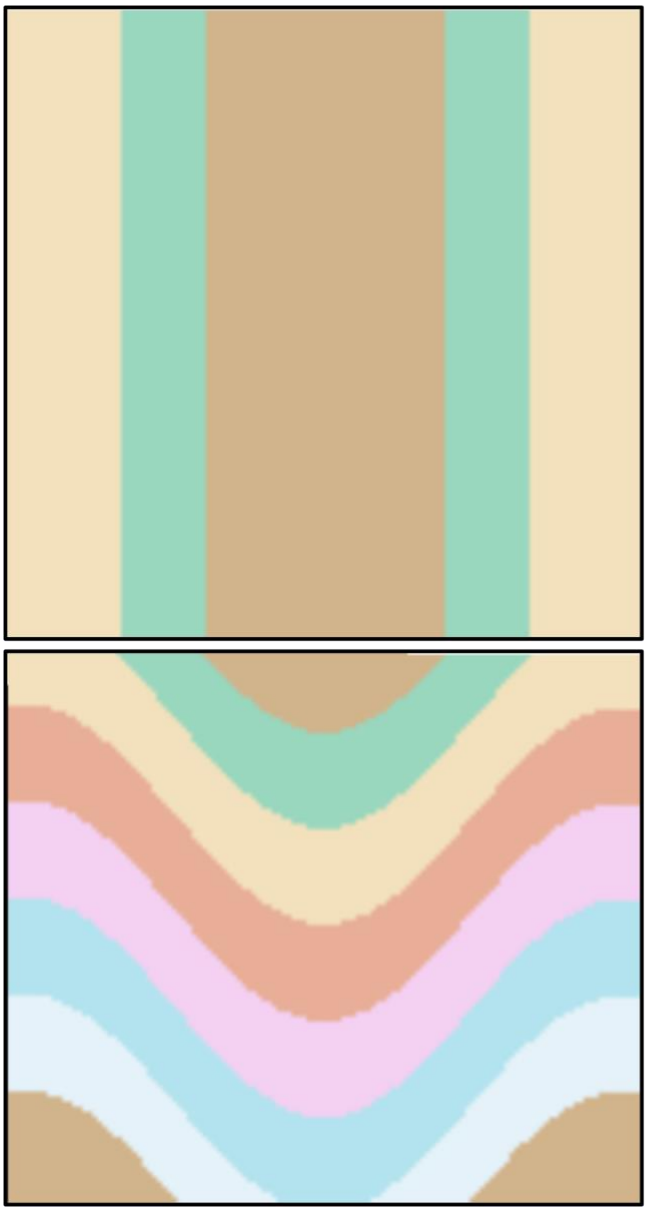


Figure 15.26: Figure for Question 2 in Activity 15B.

3. Draw the appropriate map symbols, including strike and dip, for the fold on the map view below.

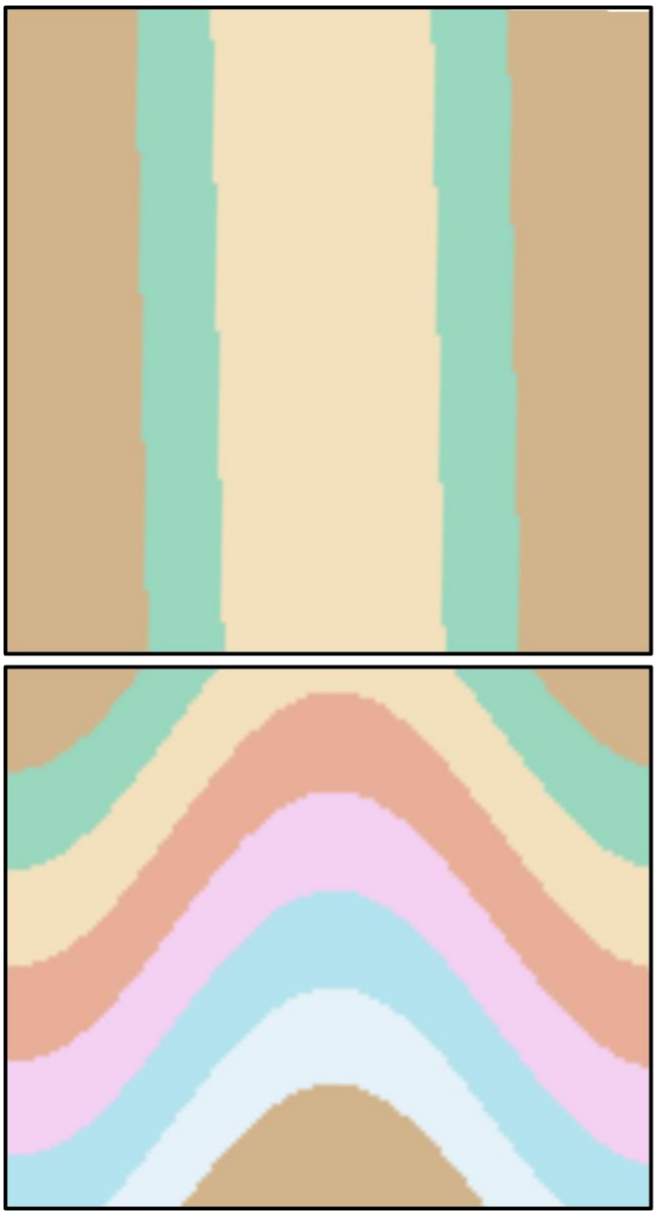


Figure 15.27: Figure for Question 3 in Activity 15B.

4. Draw the appropriate map symbols, including strike and dip, for the fold on the map view below.

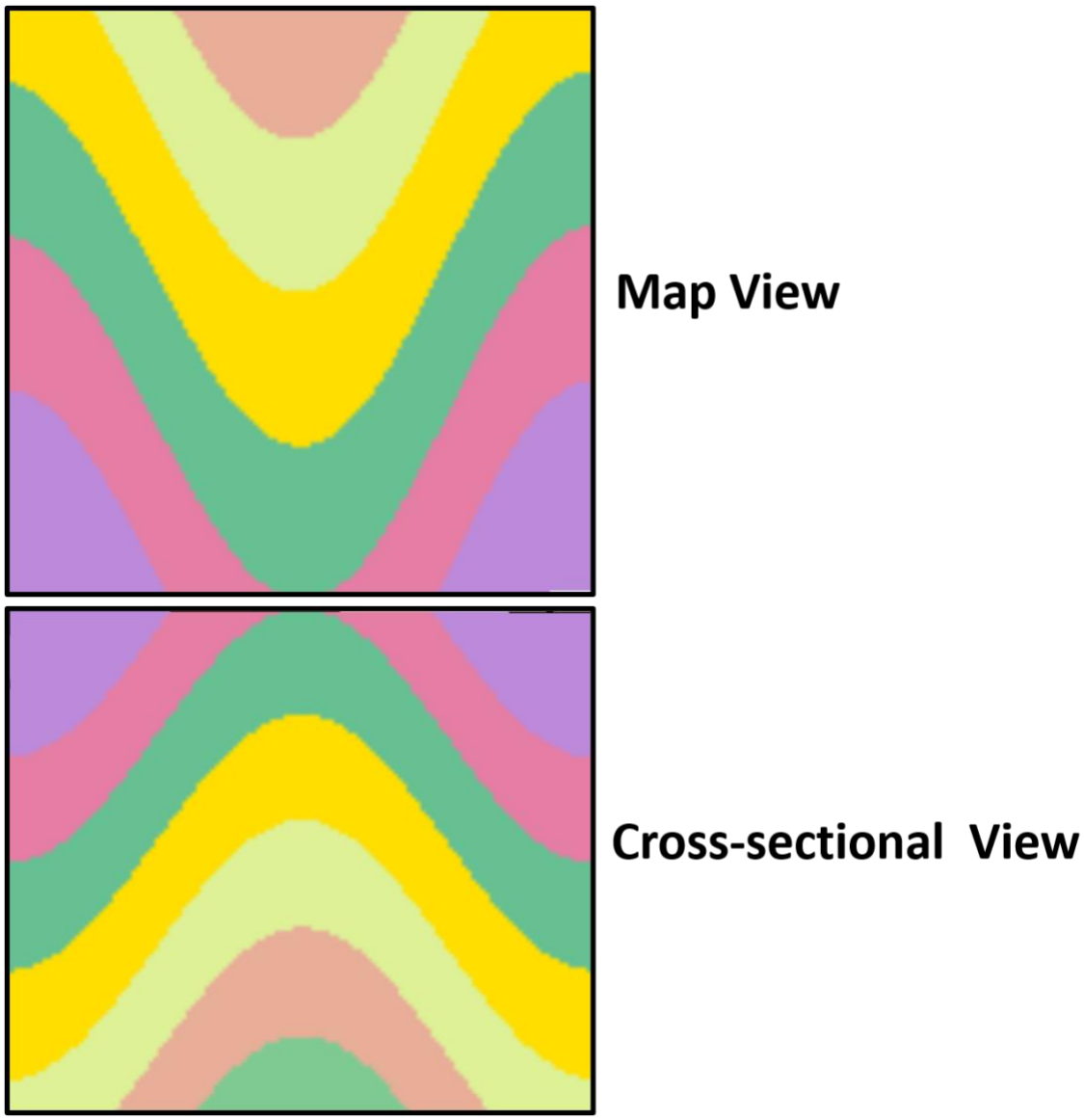


Figure 15.28: Figure for Question 4 in Activity 15B.

5. Draw the appropriate map symbols, including strike and dip, for the fold on the map view below.

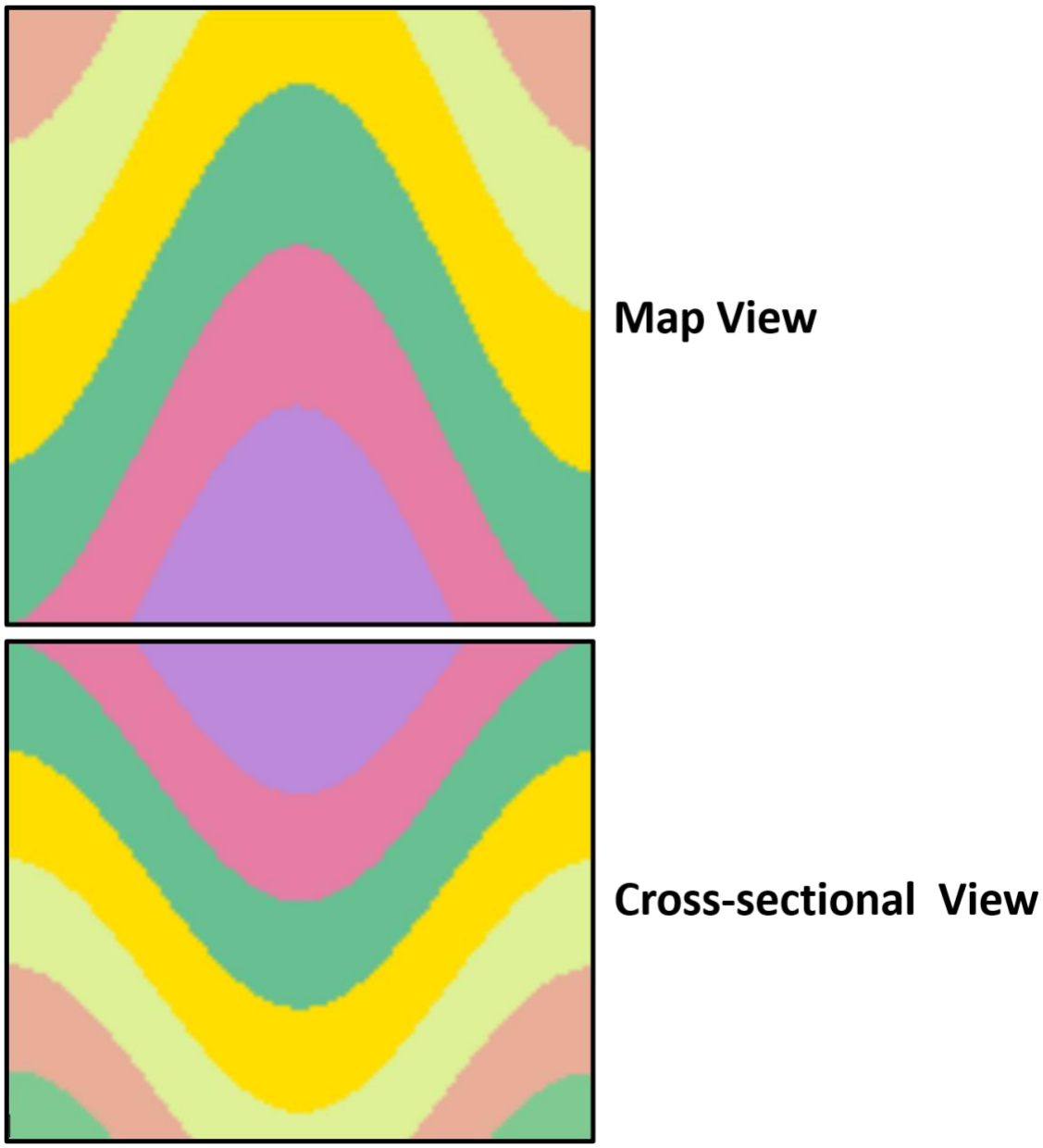


Figure 15.29: Figure for Question 5 in Activity 15B.

Attributions

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- Figure 15.27: “Block Diagram Practice #2” (CC-BY; Chloe Branciforte via Visible Geology)
- Figure 15.28: “Block Diagram Practice #3” (CC-BY; Chloe Branciforte via Visible Geology)
- Figure 15.29: “Block Diagram Practice #4” (CC-BY; Chloe Branciforte via Visible Geology)

Activity 15C: Geologic Structure Identification

1. Identify the geologic structure in **Figure 15.30** below, and the stress which formed it.
   a. Structure Name:
   b. Stress:

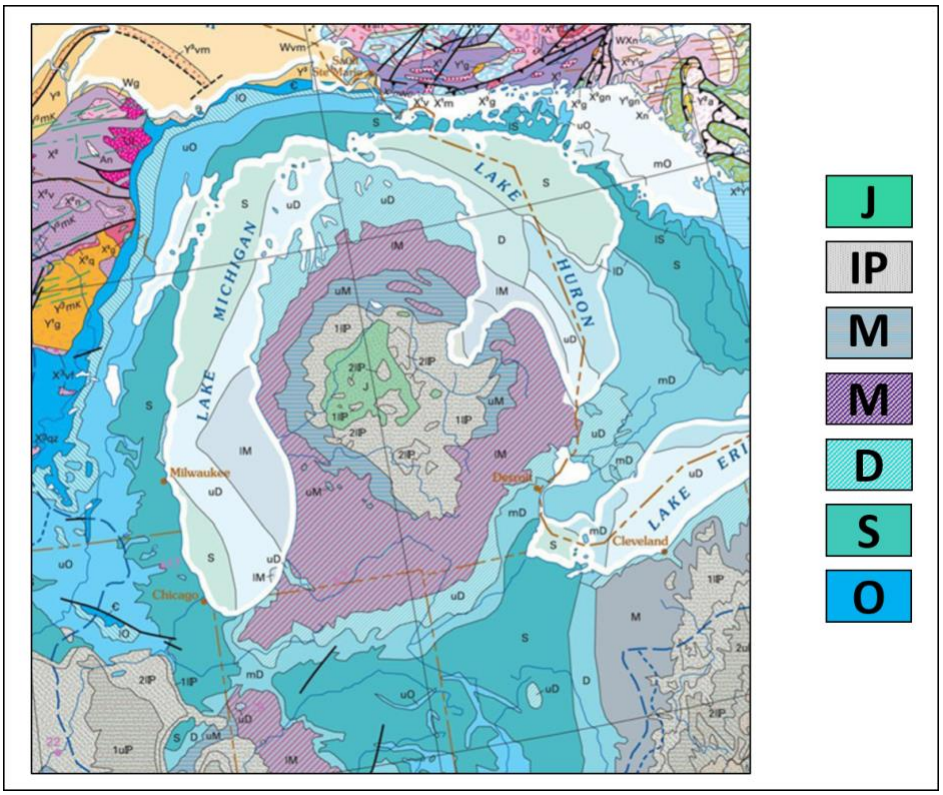


Figure 15.30: Figure for Question 1 in Activity 15C.

2. Identify the geologic structure in **Figure 15.31** below, and the stress which formed it.
   a. Structure Name:
   b. Stress:

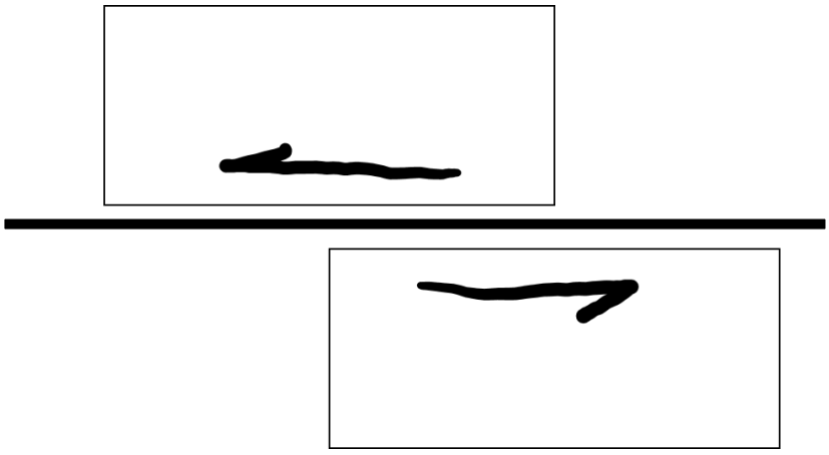


Figure 15.31: Figure for Question 2 in Activity 15C.

3. Identify the geologic structure in **Figure 15.32** below, and the stress which formed it.
   a. Structure Name:
   b. Stress:

Figure 15.32: Figure for Question 3 in Activity 15C.

4. Identify the geologic structure in **Figure 15.33** below, and the stress which formed it.
   a. Structure Name:
   b. Stress:

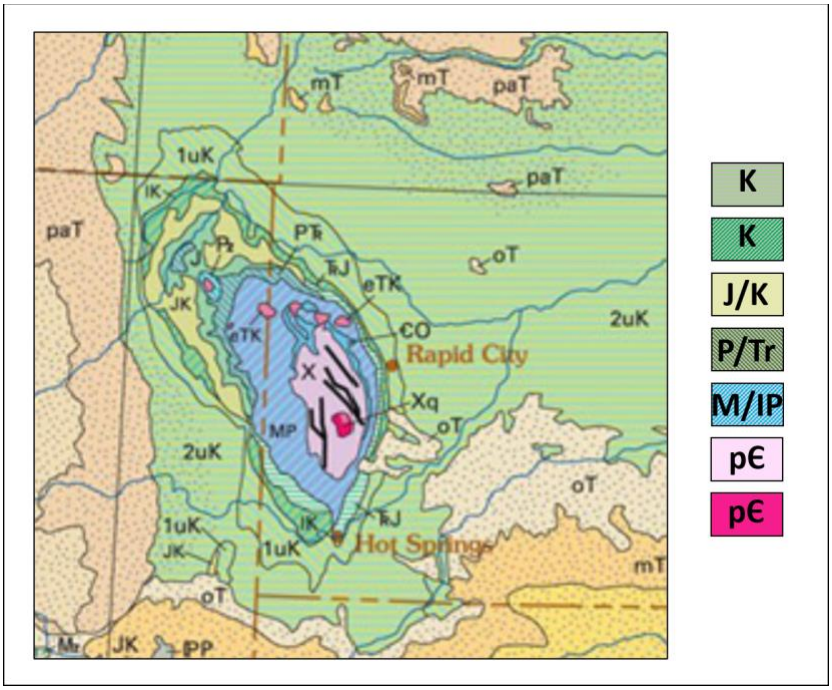


Figure 15.33: Figure for Question 4 in Activity 15C.

5. Identify the geologic structure in **Figure 15.34** below, and the stress which formed it.
    a. Structure Name:
    b. Stress:

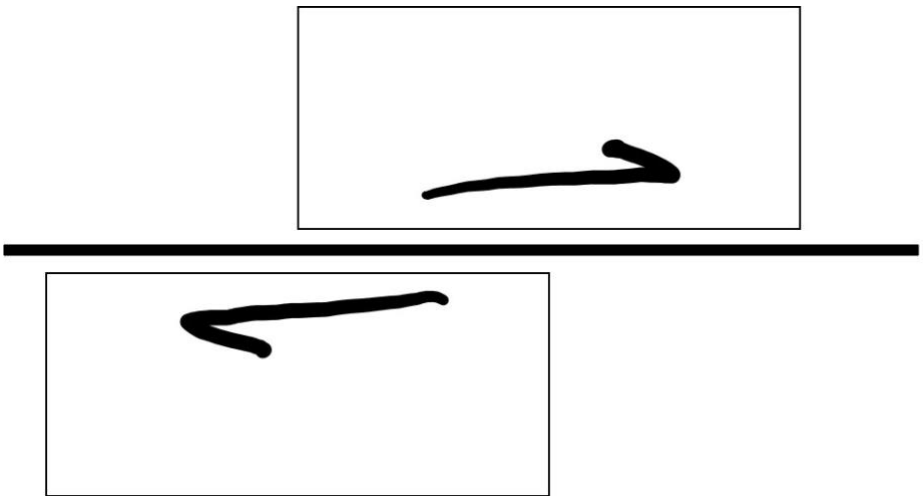


Figure 15.34: Figure for Question 5 in Activity 15C.

6. Identify the geologic structure in the cross-sectional view (**Figure 15.35**) below, and the stress which formed it.
    a. Structure Name:
    b. Stress:

Figure 15.35: Figure for Question 6 in Activity 15C.

7. Identify the geologic structure in the map-view (**Figure 15.36**) below, and the stress which formed it.
    a. Structure Name:
    b. Stress:

Figure 15.36: Figure for Question 1 in Activity 15C.

8. Identify the geologic structure(s) in **Figure 15.37** below, and the stress which formed it.
    a. Structure Names:
    b. Stress:

Figure 15.37: Figure for Question 8 in Activity 15C.

9. Identify the geologic structure(s) in **Figure 15.38** below, and the stress which formed it.

a. Structure Names:

b. Stress:

Figure 15.38: Figure for Question 9 in Activity 15C.

10. Identify the geologic structure(s) in the cross-section (**Figure 15.39**) below, and the stress which formed it.

a. Structure Names:

b. Stress:

Figure 15.39: Figure for Question 10 in Activity 15C.

Attributions

- Figure 15.30: Derivative "Geologic Map of North America" (Public Domain; USGS) by Chloe Branciforte
- Figure 15.31: "Strike-slip Fault 1" (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 15.32: "Fold in Maryland" (CC-BY-SA 3.0; Acroterion via Wikimedia Commons)
- Figure 15.33: Derivative "Geologic Map of North America" (Public Domain; USGS) by Chloe Branciforte
- Figure 15.34: "Strike-slip Fault 2" (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 15.35: "Split Mountain Gorge Fold in Anza-Borrego Desert State Park" (CC-BY-SA 4.0; Robert Arends via Wikimedia Commons)
- Figure 15.36: "Richat Structure" (Public Domain; NASA)
- Figure 15.37: Derivative of "Folded Ordovician Limestones" (CC-BY 2.0; James St. John via Flickr) by Chloe Branciforte
- Figure 15.38: "Faults, Volcanic Glass, and Tuff" (CC-BY-SA 2.0; Penny Higgins via Flickr)
- Figure 15.39: "Fault in Gyprock" (CC-BY 2.0; James St. John via Flickr)

Activity 15D: Google Earth and Structures

Using the browser version of Google Earth, search for 36°33'50.3"N 116°54'51.1"W and zoom out and make sure to note your geographic location. Zoom back into an eye altitude (camera) of 114 miles. You are looking at the surface expression of many fault lines, or what is called **fault scarp**, with the hanging wall occupying the valleys and the footwall representing the mountains.

1. What kind of faults are these?

2. What would we call these paired features?

3. Which stress type produced these features?

4. Within Badwater Basin exists the lowest elevation in North America.
    a. What is this elevation?

Search for 22°48'45.6"S 117°20'12.9"E and zoom to an eye altitude of 30 miles. This geologic structure is caused by the folding of rocks. Imagine you are a geologist trying to determine what is going on in the area.

5. Is this structure a dome or a basin? *Hint: use the street view for a better vantage*.

    a. How could you tell?

6. Provide two different ways to tell the complex folds apart.

7. Examine the geologic structure ~10 miles southwest of the previous feature. Is this fold horizontal or plunging, how can you tell?

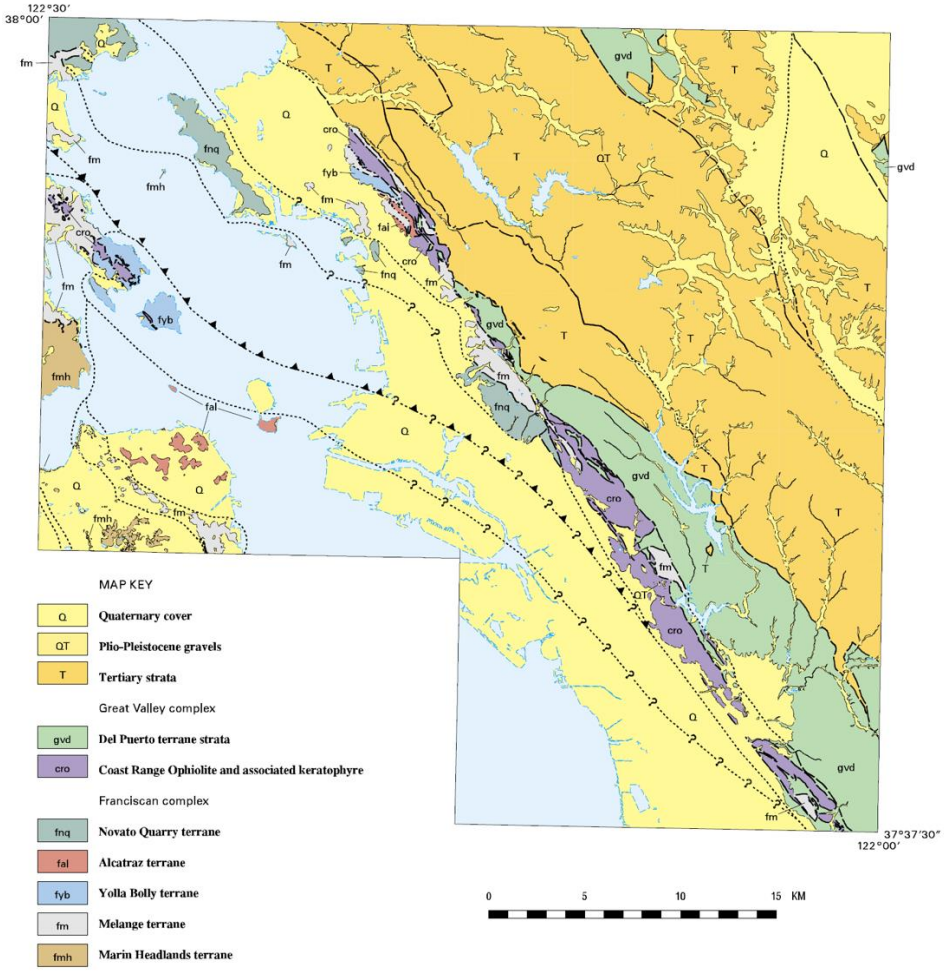
Chapter 16: Geologic Maps

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Use legends and symbols to interpret geologic maps.
- ✔ Measure strike and dip using the quadrant and azimuth systems.
- ✔ Construct and interpret a geologic cross-section.

Thumbnail for Chapter 16:



Thumbnail: Derivative of "Geologic Map and Map Database of the Metropolitan Area, Alameda, Contra Costa, and San Francisco Counties, California" (Public Domain; R.W. Gramer/USGS) by Chloe Branciforte

What Are Geologic Maps and Why Are They Important?

A **geologic map** uses lines, symbols, and colors to illustrate information about the nature and distribution of rock units within an area (**Figure 16.1**). Typically, a geologic map will depict mappable rock or sediment units. A **mappable unit** of rock or sediment is one that a geologist can consistently recognize, trace across a landscape, and describe so that other geologists may recognize and verify its presence and identity. Generally, a mappable unit is a **geologic formation**. These mappable units are shown as different colors or patterns on a base map (usually a **topographic map**), over which information about geologic contacts and strikes and dips are included. Geologists make these maps by making careful field observations at numerous **outcrops** (exposed rocks at the Earth's surface) throughout the mapping area. At each outcrop, geologists record information such as rock type, strike and dip of the rock layers, and relative age data. Geologic maps take practice to understand, since they display three-dimensional features, such as folds, on a two-dimensional surface.

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, engineering, and hazard assessment. Geologic maps are also vital in finding and developing geological resources, such as sediments, groundwater, fossil fuels, and minerals.

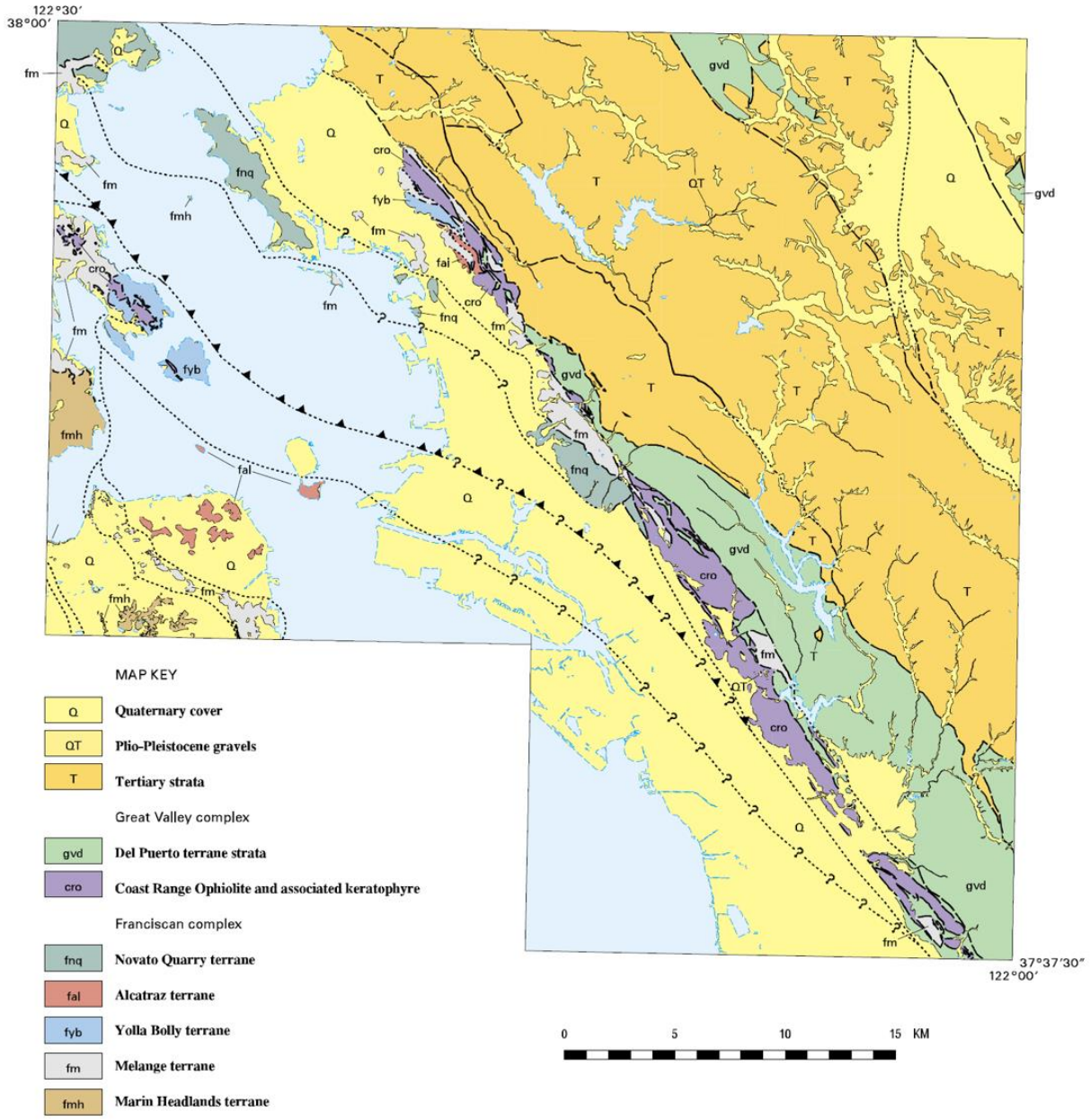


Figure 16.1: Simplified geologic map illustrating Mesozoic terranes in and around the Bay Area.

Attributions

- Figure 16.1: Derivative of “Geologic Map and Map Database of the Metropolitan Area, Alameda, Contra Costa, and San Francisco Counties, California” (Public Domain; R.W. Gramer/USGS) by Chloe Branciforte

What Are the Essential Components of Geologic Maps?

Most geologic maps have the following features (**Figure 16.2**):

1. The map itself
2. The map legend or key that explains all the symbols on the map
3. Geologic cross-section(s) of the map area. These will be explored further in the next chapter.

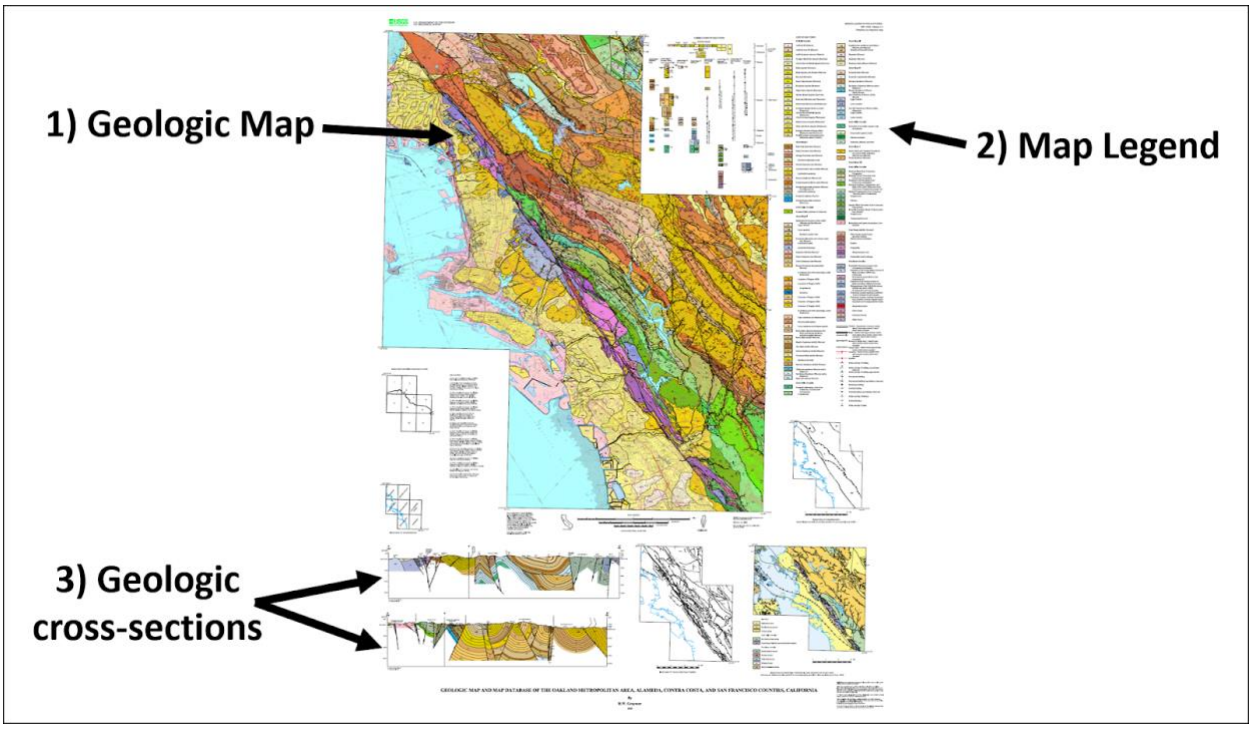


Figure 16.2: 1) Geologic map, 2) legend and 3) cross-sections.

Attributions

- Figure 16.2: Figure 15.20: Derivative of “Geologic Map and Map Database of the Metropolitan Area, Alameda, Contra Costa, and San Francisco Counties, California” (Public Domain; R.W. Gramer/USGS) by Chloe Branciforte

What Is a Geologic Map Legend?

The map legend to a geologic map is usually printed on the same page as the map and follows a customary format (**Figure 16.3**).

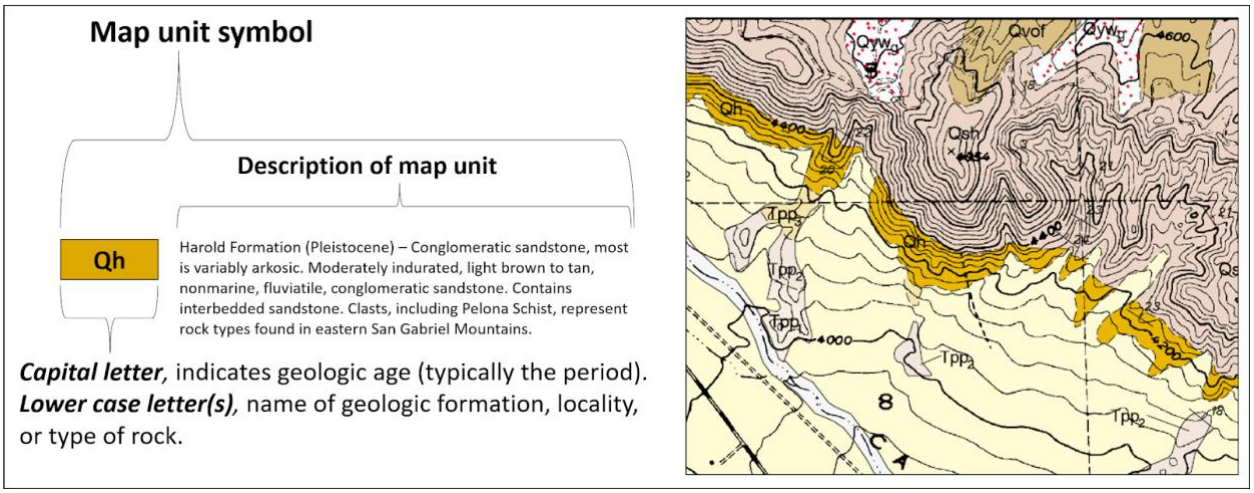


Figure 16.3: General formatting for the legend of a geologic map.

The symbol for each formation, or unit, is shown in a box next to its name with a brief description. The symbols typically follow superposition and are stacked in an age sequence from oldest at the bottom to youngest at the top. This allows the map reader to quickly assess the relative age of each unit. The geologic age (typically the geologic period) is listed for each unit in the key and uses standard symbols (**Table 16.1**). The map legend also contains an explanation of the symbols shown on the map, such as the symbols for different types of faults and folds (**Table 16.2**). The explanations of rock units often follow the map symbol on the map, but for very large maps 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.

Relative Age	Geologic Age Symbol	Geologic Time Period
Younger	Q	Quaternary
	T	Tertiary
	K	Cretaceous
	J	Jurassic
	Tr	Triassic
	P	Permian
	IP	Pennsylvanian
	M	Mississippian
	D	Devonian
	S	Silurian
	O	Ordovician
	Є	Cambrian
Older	pЄ	Precambrian

Table 16.1: General geologic age symbols.

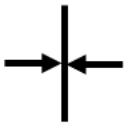
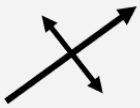
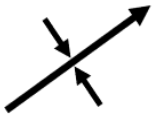
Map Symbol	Symbol Explanation
	Strike & Dip
	Vertical strata
	Horizontal strata
	Anticline axis
	Syncline axis
	Plunging anticline axis
	Plunging syncline axis
	Fault
	Strike-slip fault
	Normal fault
	Reverse fault

Table 16.2: General geologic map symbols.

Attributions

- Figure 16.3: Derivative of “Geologic Map of the Telegraph Peak 7.5’ Quadrangle, San Bernardino County, California” (Public Domain; D.M Morton, M.O Woodburne, and J.H. Foster/USGS) by Chloe Branciforte
- Table 16.1: “Geologic Age Symbols” (CC-BY; Chloe Branciforte, own work)
- Table 16.2: “Geologic Map Symbols” (CC-BY; Chloe Branciforte, own work)

What Is a Geologic Cross-section?

Remember that a geologic map will be seen in map-view. However, geologists use information about rocks that are exposed at the surface to visualize the unseen rocks beneath the surface, enabling them to also construct a cross-sectional view. A **geologic cross-section** illustrates how different types of rock are layered or otherwise configured, including geologic structures, such as folds and faults (**Figure 16.4**).

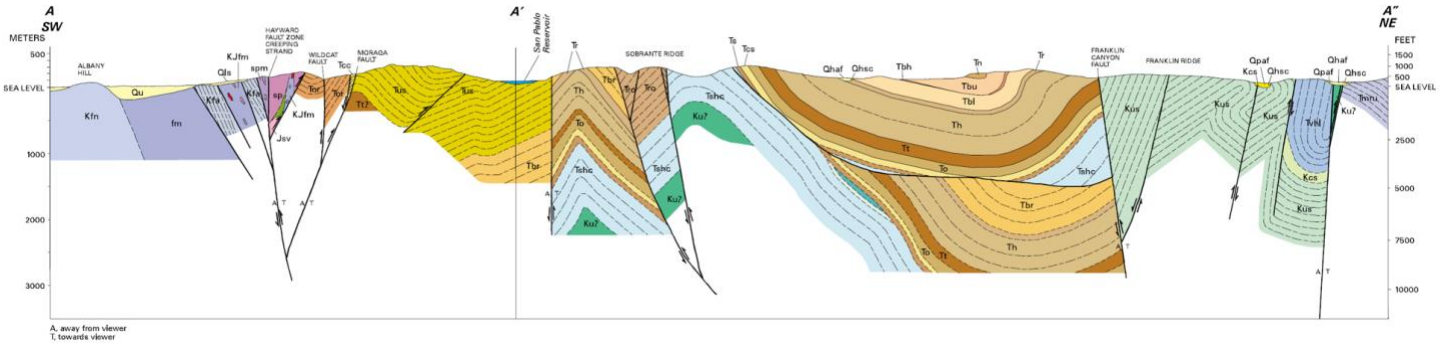


Figure 16.4: Geologic cross-section (A-A'-A") from the northern section of the Alameda, Contra Costa, and San Francisco Counties, California geologic map.

Attributions

- Figure 16.4: Derivative of “Geologic Map and Map Database of the Metropolitan Area, Alameda, Contra Costa, and San Francisco Counties, California” (Public Domain; R.W. Gramer/USGS) by Chloe Branciforte

How Do I Construct a Geologic Cross-section?

Follow these steps to successfully create your own geologic cross-section (**Figure 16.5**):

1. Locate the points between which you will be constructing a cross-section for. Observe the geologic map in this region. Pay close attention to any strike and dip symbols, geologic contacts, and ages of the rock types.
2. Take a sheet of scrap (scratch) paper. Place the paper along the map where you want to draw a cross-section.
3. At each geologic contact, make a mark on the scratch paper. Position the marks in the direction you believe the rocks are dipping. To determine this, use any strike and dip symbols. If they are not provided, use the Rule of V's or the ages given to help determine the geologic structure.
4. Transfer the marks from your paper to a provided diagram.
5. Sketch in and complete any structures, paying careful attention to dip angles (if provided). Structures may be drawn in with a dotted line above the Earth's surface to indicate rocks that were formerly present but that have since been eroded.
6. Incorporate a legend into the cross-section to explain the types of geologic materials present.
7. Include vertical and horizontal scales along with the statement of vertical exaggeration.

Need more information? Watch the construction of a cross-section **in this YouTube video.**

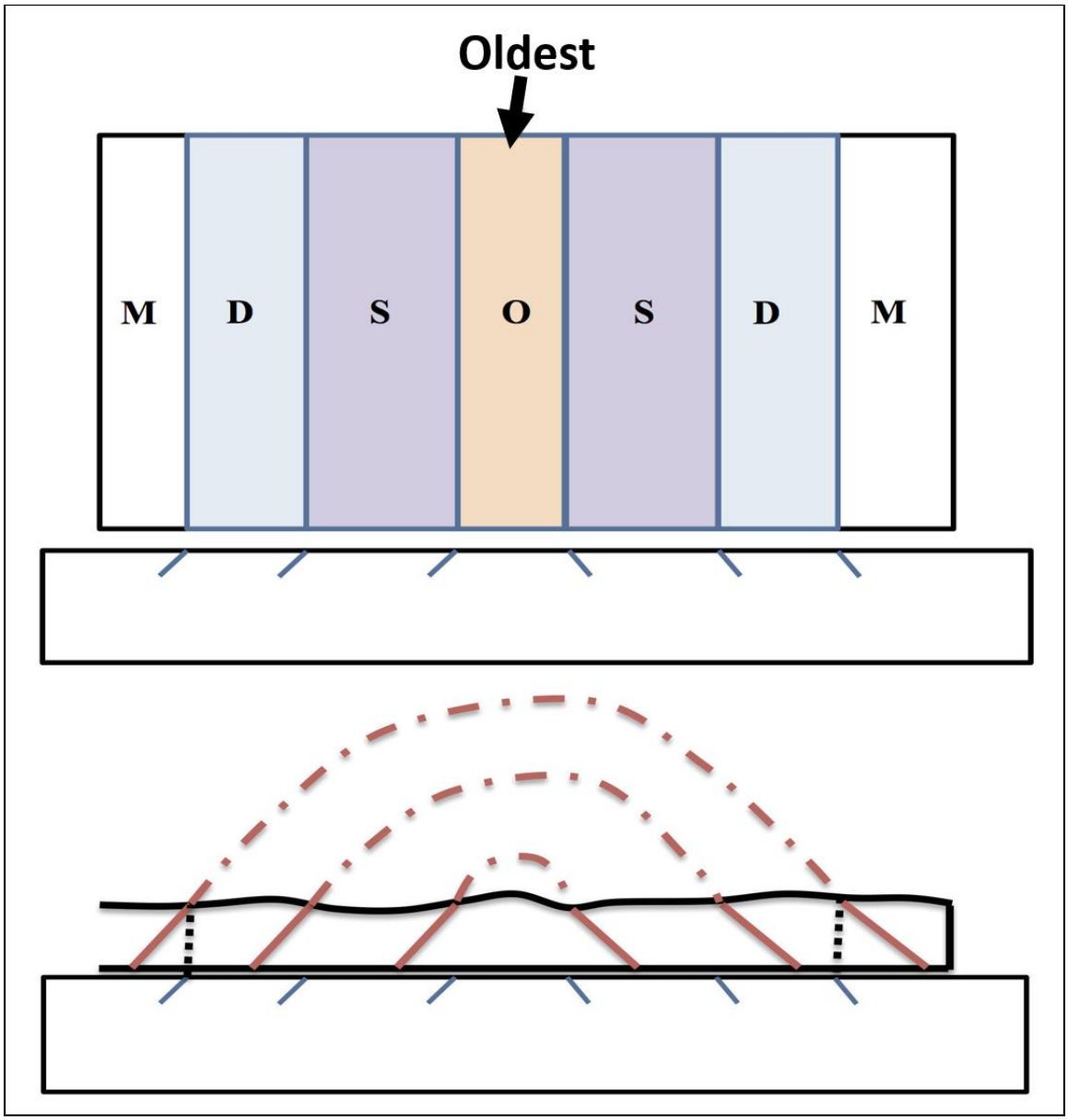


Figure 16.5: How to construct a geologic cross-section from a geologic map.

Attributions

- Figure 16.5: Derivative of “Geologic Map to Cross-section” (CC-BY-SA 3.0; Randa Harris via LibreText) by Chloe Branciforte

General Rules for Interpreting Geologic Maps

- **Folds:**
    - **Anticlines** have their oldest beds in the center, and their limbs (sides) dip away from the fold axis or hinge. **Plunging anticlines** plunge towards the closed end (nose) of the V-shaped outcrop belt.
    - **Synclines** have their youngest beds in the center, and their limbs (sides) dip toward the fold axis or hinge. **Plunging synclines** plunge toward the open end of the V-shaped outcrop belt.
- **Streams:**
    - They intersect dipping beds of rock, they will cut V shapes in the direction of dip.
    - They cut "V" shapes into horizontal beds and formation contacts that point upstream. The formation contacts are parallel to topographic contour lines, and the stream drainage system developed on horizontal and/or unstratified formations has a dendritic pattern that resembles the branching of a tree.
    - They cut across vertical beds, there will not be a V-shape
- **Faults:**
    - Upthrown blocks of faults tend to be eroded more (down to older beds) than downthrown blocks.
- **General:**
    - Geologic contacts migrate downdip upon erosion.
    - True dip angles can only be seen in cross-section if the cross-section is perpendicular to the fault or to the strike of the beds.

Strike and Dip

Recall that the symbol for strike and dip is given along the top of the block, as shown in **Figure 16.6**. Note that the dip symbol (shorter line) is perpendicular to the strike symbol; dip degree (number) will vary depending on measurements.

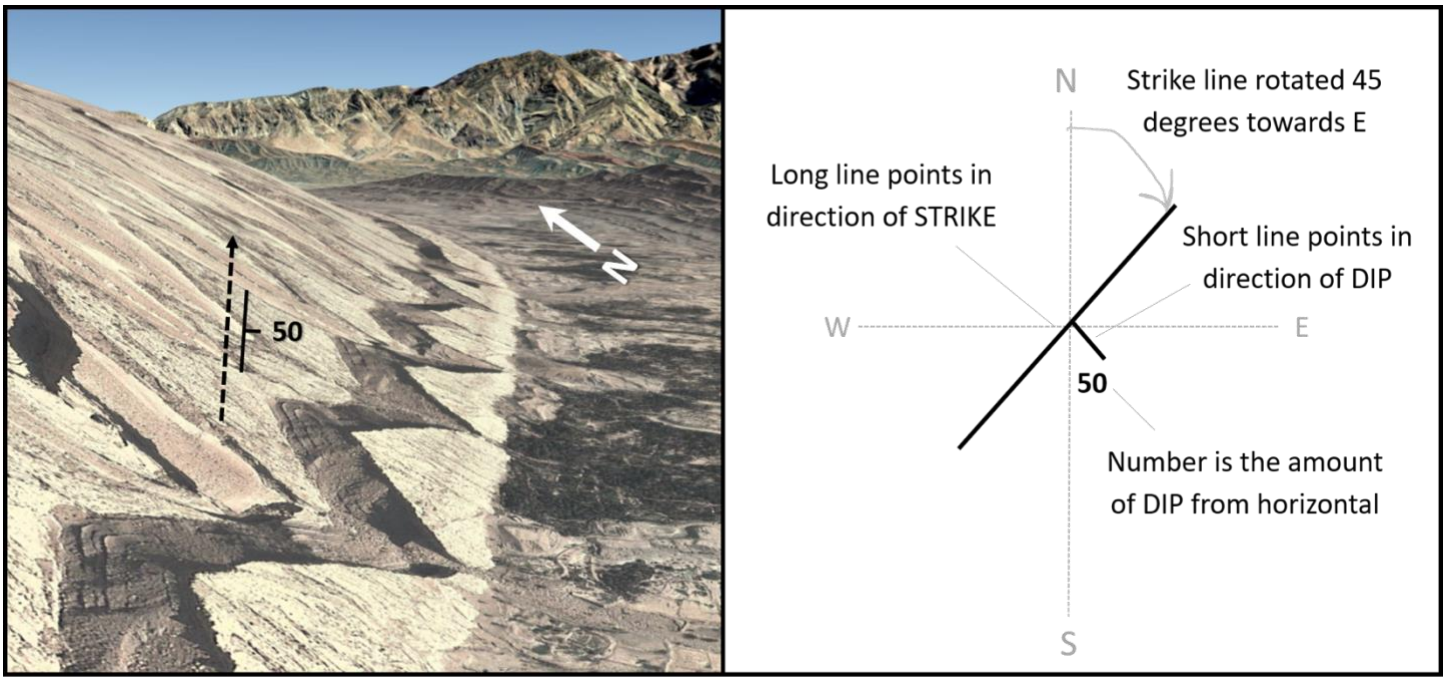


Figure 16.6: *Right*, a strike and dip symbol on tilted sedimentary beds. *Left,* the strike and dip symbol from the diagram on at compass rose to illustrate directional and use of the symbol.

Attributions

- Figure 16.6: “Strike and Dip” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)

Strike and Dip Measurement

Geologists typically use a **Brunton compass** to measure strike and dip (**Figure 16.7**). **Strike** is measured along the plane by using the leveling bubble on the compass. **Dip** is measured by laying the side of the compass perpendicular to the strike measurement and rotating the horizontal level until the bubble is stable and the reading has been made.

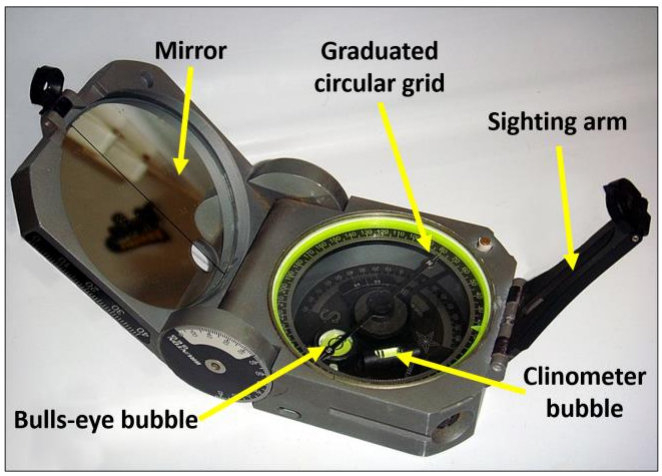


Figure 16.7: A Brunton Pocket Transit, a specialized compass used by geologists and other field-based surveying over long distances.

Recording strike and dip can be done using two different systems, the **Azimuth System** or the **Quadrant System** (**Figure 16.8**), and the choice between the two is dependent on the geologist, location, or organization for which the data is collected or produced. A strike can be given as a quadrant compass bearing of the strike line (N25E for example) or using a single three-digit number representing the azimuth, where the lower number is usually given. In our example of N25E, the azimuth reading would be 025° (see **Table 16.2** for other examples.) Some students will find they prefer one system over the other. This is typically a personal decision; however, many geologists (and geology majors) find it important to know both systems, as they may be asked to use both over the course of their career.

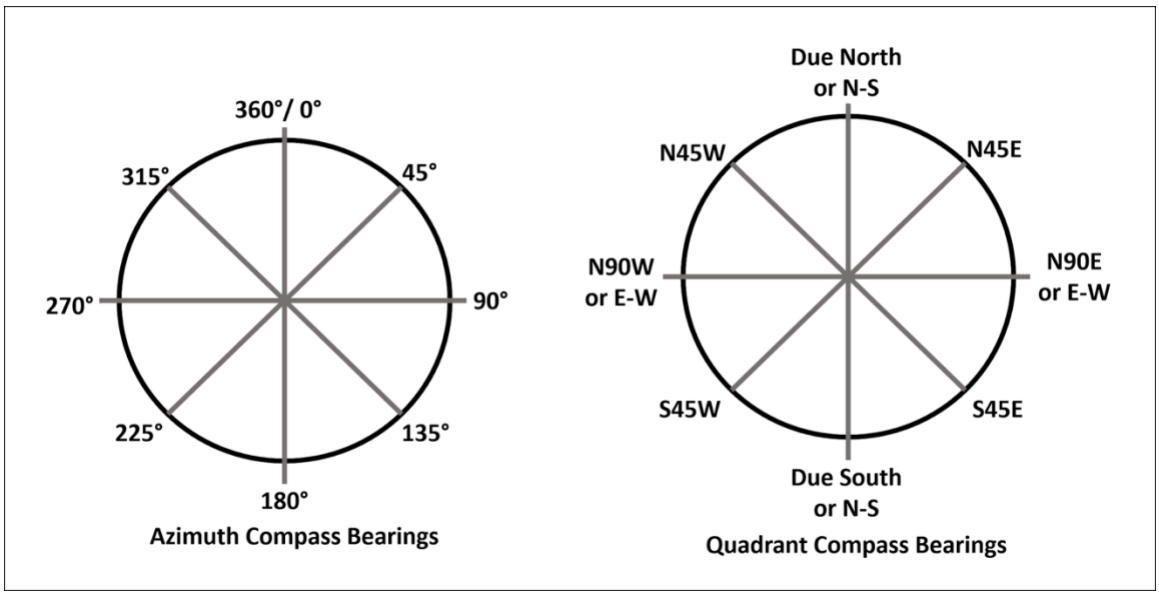


Figure 16.8: *Left*, azimuth compass bearings. *Right*, quadrant compass bearings.

System	Strike & Dip	Description
Quadrant	N50W, 78NE	--
	N70E, 30SE	--
	N90W, 33N	Strike direction, due west. Dip direction, due north.
	N70W, 90	Vertical dips have no quadrant direction.
Azimuth	315, 78NE	--
	70, 30S	--
	270, 33N	--
	290, 90	--

Table 16.3: Compass systems and their relationship to strike and dip.

Attributions

- Figure 16.7: Derivative of “Brunton” (CC-BY-SA 3.0; Matt Affolter (QFL247) via Wikimedia Commons) by Chloe Branciforte
- Figure 16.8: “Azimuth and Quadrant Compass Bearings” (CC-BY; Chloe Branciforte, own work)
- Table 16.3: “Compass Systems” (CC-BY; Chloe Branciforte, own work)

How Do I Draw a Strike and Dip Symbol?

Using the **quadrant system**, a geologist measured the strike and dip of a rock layer as **N35W, 30 NE**. How can we draw a strike and dip symbol for this measurement?

- Sketch a light grid on your paper, and label the directions, North, East, South, West (**Figure 16.9**).
- Using a protractor, place the small center hole or point over the place where you'll draw the strike line, usually near the center of your grid. Lightly mark this location with a dot.
- Align the straight edge of the protractor so that it's pointed due north, typically toward the top of the page. Since this quadrant measurement has a strike to the NW, place the protractor so that it makes the shape of a capital D. If you have a full 365° protractor, you do not need to be concerned with the overall shape. However, for both protractor types be sure 0° is towards the top of the page (**Figure 16.10, left**). Lightly mark the 0° point.

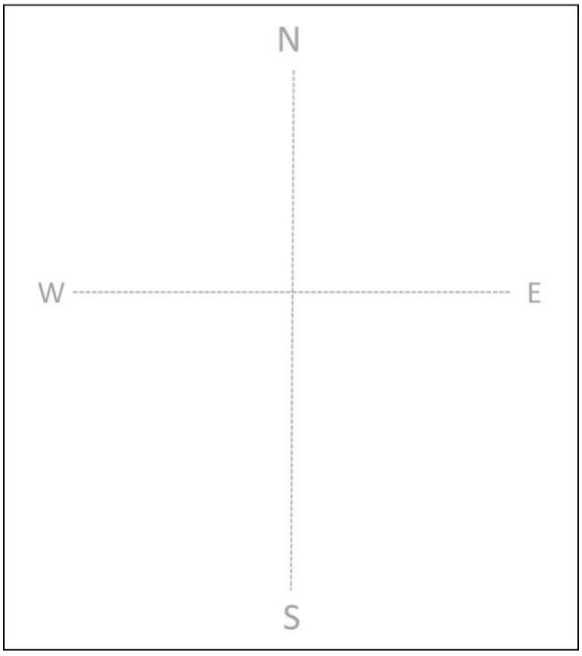


Figure 16.9: Grid set-up for drawing strike and dip symbols.

- Rotate the protractor 35° toward the west (to the left) until the 35° marking is aligned with true north. Be sure to read the outside numbers. Lightly mark the 35° point. The straight edge of the protractor is now aligned with a N35W strike.
- Lightly connect the marks you've previously made with a line along the straight edge of the protractor. To create a final strike line, darken about a centimeter or so of this line towards the center of your grid. This line is now the strike line for N35W (**Figure 16.10, center**).
- Now, the dip direction and measurement need to be added to complete the symbol. Determine the correct dip direction based on the measurement and the grid you've drawn. In this example, the dip is toward the NE, which is on the right side of the strike line. Remember, dip is perpendicular to strike. The dip line should be about 0.5 centimeter or less in length and should be perfectly straight and perpendicular from the strike line. Lastly, add the dip measurement, in this case 30°, typically this is written without a degree symbol (**Figure 16.10, right**).

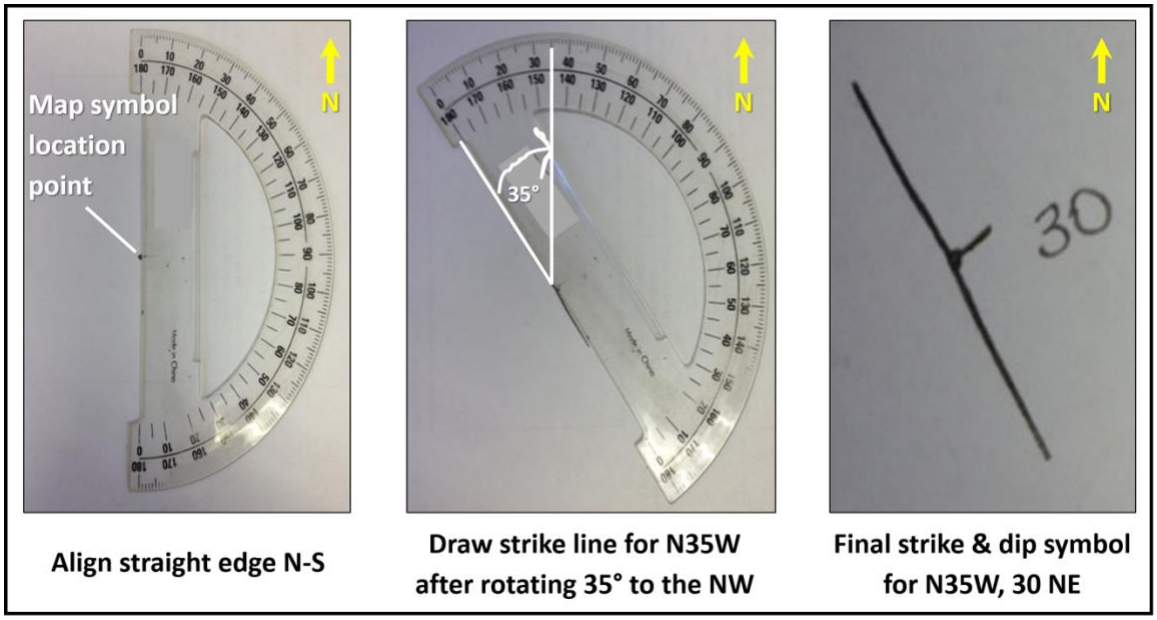


Figure 16.10: How to use a protractor to measure strike and dip using the quadrant system.

Using the **azimuth system**, a geologist measured the strike and dip of a rock layer as **330°, 30 NE**. How can we draw a strike and dip symbol for this measurement?

- Sketch a light grid on your paper, and label the directions, North, East, South, West (**Figure 16.9**).
- Using a full 365° protractor, place the small center hole or point over the place where you'll draw the strike line, usually near the center of your grid. Lightly mark this location with a dot.
- Since we are now using the azimuth system, we need to measure 330° with our protractor. If you are using a half protractor, you will need to make a capital D again and subtract 330°from 365°. For both protractor types, be sure 0°/360° is towards the top of the page (**Figure 16.11, left**). Lightly mark the 0° point.
- Use the inside numbers to measure 330° with the full protractor. If you have the half-protractor, you must subtract 330° from 365° and then measure the resulting angle of 35° (rotate towards the west). Lightly mark this point. The straight edge of the protractor is now aligned with a 330° strike.
- Lightly connect the marks you've previously made with a line along the straight edge of the protractor. To create a final strike line, darken about a centimeter or so of this line towards the center of your grid. This line is now the strike line for 330° (**Figure 16.11**).
- Now, the dip direction and measurement need to be added to complete the symbol. Determine the correct dip direction based on the measurement and the grid you've drawn. In this example, the dip is toward the NE, which is on the right side of the strike line. Remember, dip is perpendicular to strike. The dip line should be about 0.5

centimeter or less in length and should be perfectly straight and perpendicular from the strike line. Lastly, add the dip measurement, in this case 30°, typically this is written without a degree symbol (**Figure 16.11, right**).

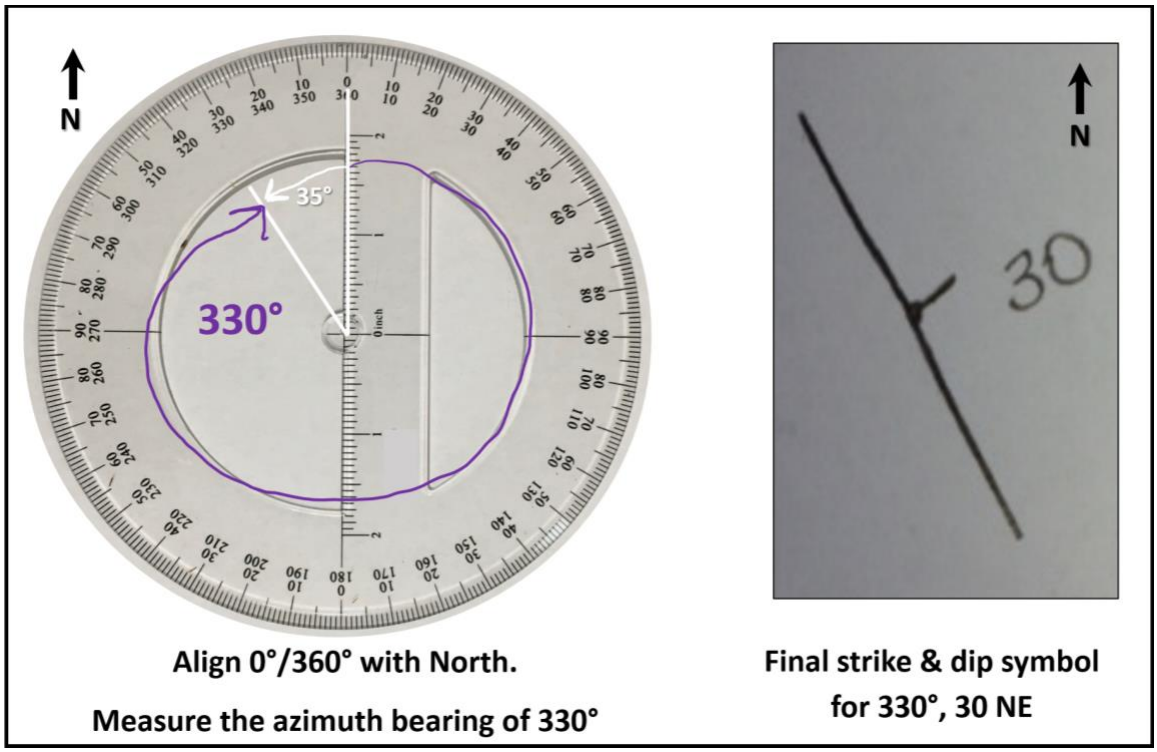


Figure 16.11: How to use a protractor to measure strike and dip using the azimuth system.

Attributions

- Figure 16.9: “Grid” (CC-BY; Chloe Branciforte, own work)
- Figure 16.10: “180 protractor and Strike and Dip” (CC-BY; Chloe Branciforte, own work)
- Figure 16.11: “365 protractor and Strike and Dip” (CC-BY; Chloe Branciforte, own work)

Activity 16A: Navigating the Azimuth and Quadrant Systems

1. The figure below shows the relationship between azimuth and compass quadrant bearings. In the table you will find strike measurements recorded using both systems. In the blank boxes determine the correct measurement to properly navigate between the two systems.

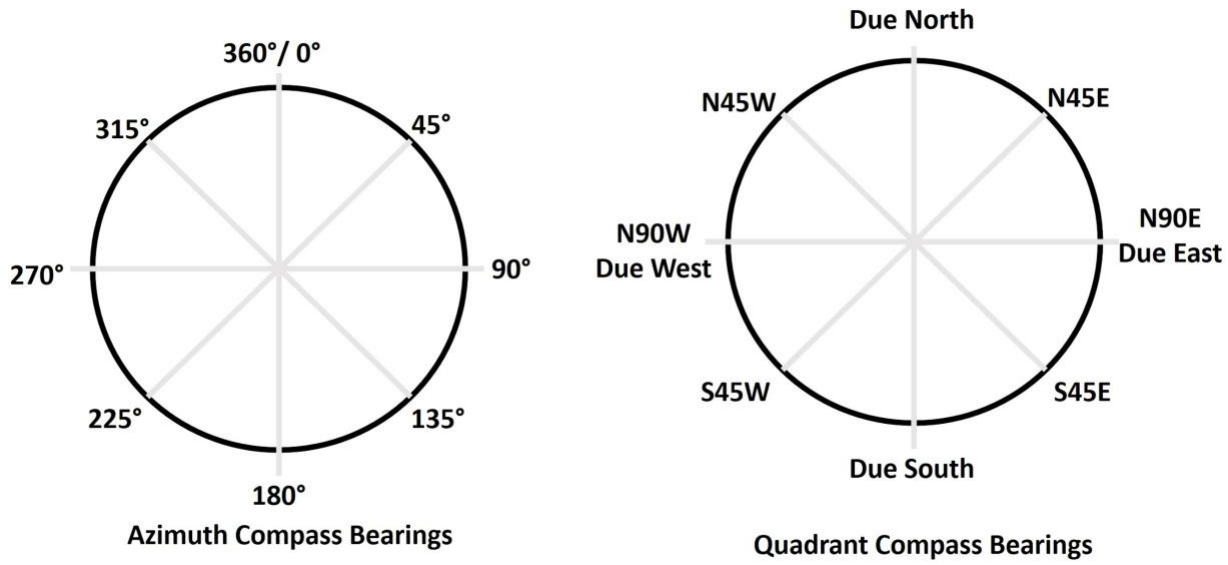


Figure 16.12: Figure for Question 1, Activity 16A.

Quadrant	Due North		N20W		S52W		Due East		N88E	
Azimuth		110°		270°		77°		305°		180°

Table 16.4: Table for Question 1, Activity 16A.

Attributions

- Figure 16.12: “Navigating Compass Bearings” (CC-BY; Chloe Branciforte, own work)
- Table 16.4: “Navigating the Compass Systems” (CC-BY; Chloe Branciforte, own work)

Activity 16B: Strike and Dip

For this section, you will need the following materials:

- Protractor, a round protractor is preferred.
- Pencil.

Let's first practice drawing strike and dip symbols.

1. Draw the map symbol for a rock unit having a strike and dip of N65E, 30 SE.

2. Draw the map symbol for a rock unit having a strike and dip of N80W, 55 NE

3. Draw the map symbol for a rock unit having a strike and dip of 125°, 25 NW.

4. Draw the map symbol for a rock unit having a strike and dip of 235°, 30 SE.

Activity 16C: Geologic Map of California

Use the online Geologic Map of California or a print version provided by your instructor to answer the following questions.

View both the map and description of map units. If you are using the browser version of the map, click on the symbol to locate the "Description of Map Units". If you have a print version, the map unit section should be clearly marked. If you are using the browser version, be sure to zoom in to see additional symbology appear on the map itself.

1. What is the geologic age of the oldest rocks on the map?

2. What is the geologic age of the youngest rocks on the map?

3. What general color are the Mesozoic plutonic granitic rocks?

4. Locate the map unit symbol for Mesozoic Plutonic rocks that are ultramafic. Where are the majority of these rocks located within California?

5. Draw the symbol for a thrust fault:

Locate the area or region where your college or university is located.

6. What is the main geologic age of the rocks in your area? If there are several, write down the top three.
7. Are there any major faults in your area? Circle an answer ***YES*** ***NO***
    a. **If you said yes**, identify at least one fault by name.
    b. **If you said no**, locate and identify the nearest fault.

Locate the Great Central Valley.

8. What is the geologic age of the rocks with the Central Valley?

9. Locate Sutter Buttes at the northern end of the Central Valley.
    a. What type of rocks dominate this feature?

b. What geologic age are these rocks?

Locate the Transverse Ranges (North of Los Angeles).

10. What do you notice about the orientation of the Transverse Ranges relative to the rest of the state's features?

11. What could be causing this orientation?

Locate the Death Valley Fault, which is southeast of the Sierra Nevada mountains and West of Henderson, Nevada. Zoom into this region.

12. What category of fault is the Death Valley Fault?

a. Draw the symbol.

13. What fold type is located west of the Death Valley Fault.

a. Draw the symbol.

Activity 16D: Murky Mists Mountain Geologic Map and Cross-section

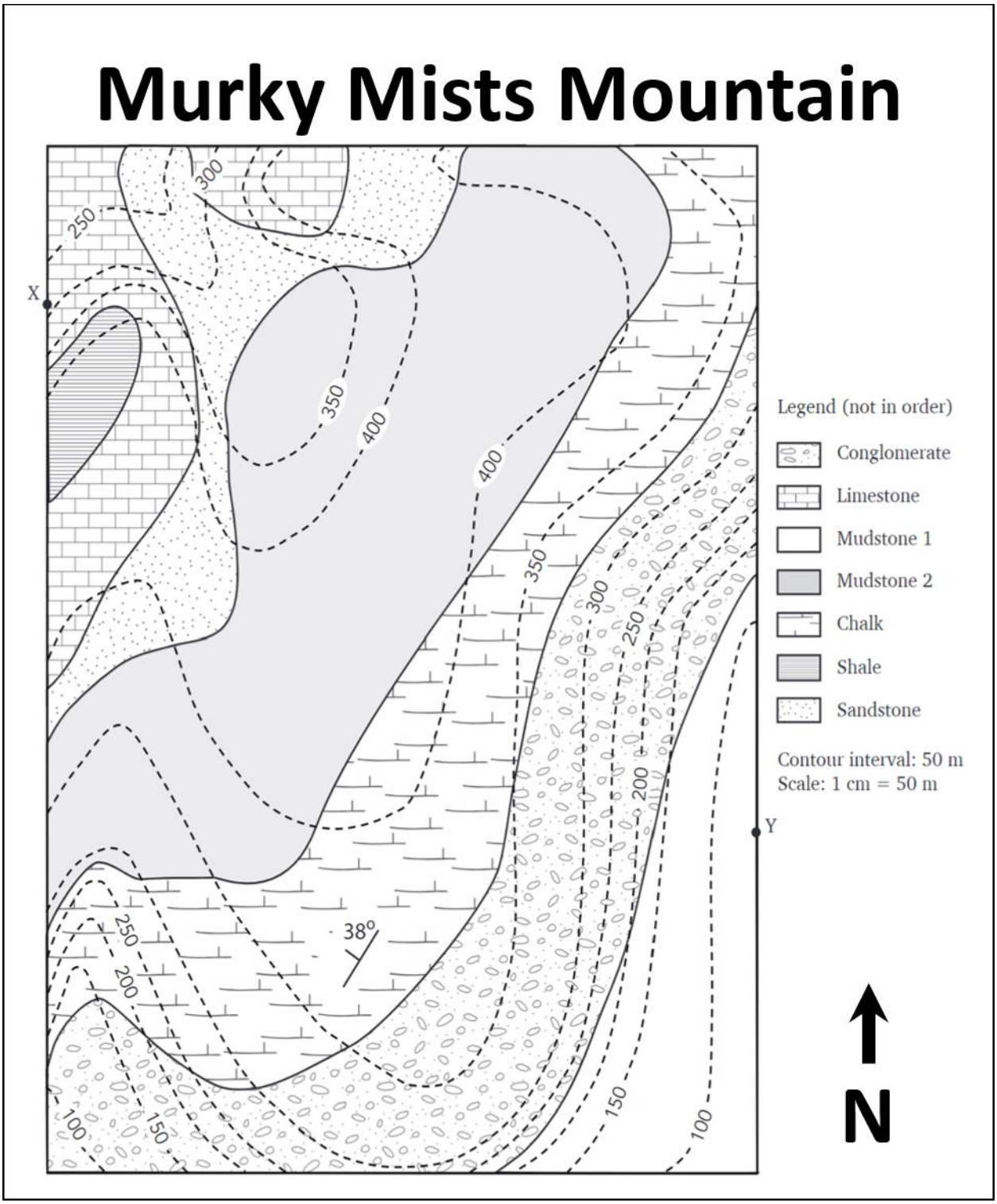


Figure 16.13: Figure for Questions 1-7, Activity 16D.

1. Examine the map of the Murky Mists Mountain. Refer to the map legend. What kind of rocks are found in this map area (circle all that apply),
    a. Sedimentary
    b. Igneous
    c. Metamorphic

2. How many units can you see?

3. Note the strike and dip symbol on the map. Presume that the units all have identical strike and dip. Which direction are the units striking and dipping?

4. Examine the contour lines on the map (dashed lines).
    a. Where are the highest points on the map?

    b. Where are the lowest points on the map?

5. Note the scale of the map. What is the distance in meters between point X and point Y?

6. If you walk from X to Y, in what direction are you walking?

7. Prepare a cross-section through the map from position X to Y (X-Y) using the cross-section template we have provided. Do not forget to indicate the X and Y positions on your cross-section. Also, add a scale bar and the ratio scale, legend, and a title. Remember to add these critical components of a cross-section, legend, orientation, title, scale. *Note: ensure your vertical scale and horizontal scale are the same, and order the units in your legend with the oldest at the bottom and the youngest at the top.*

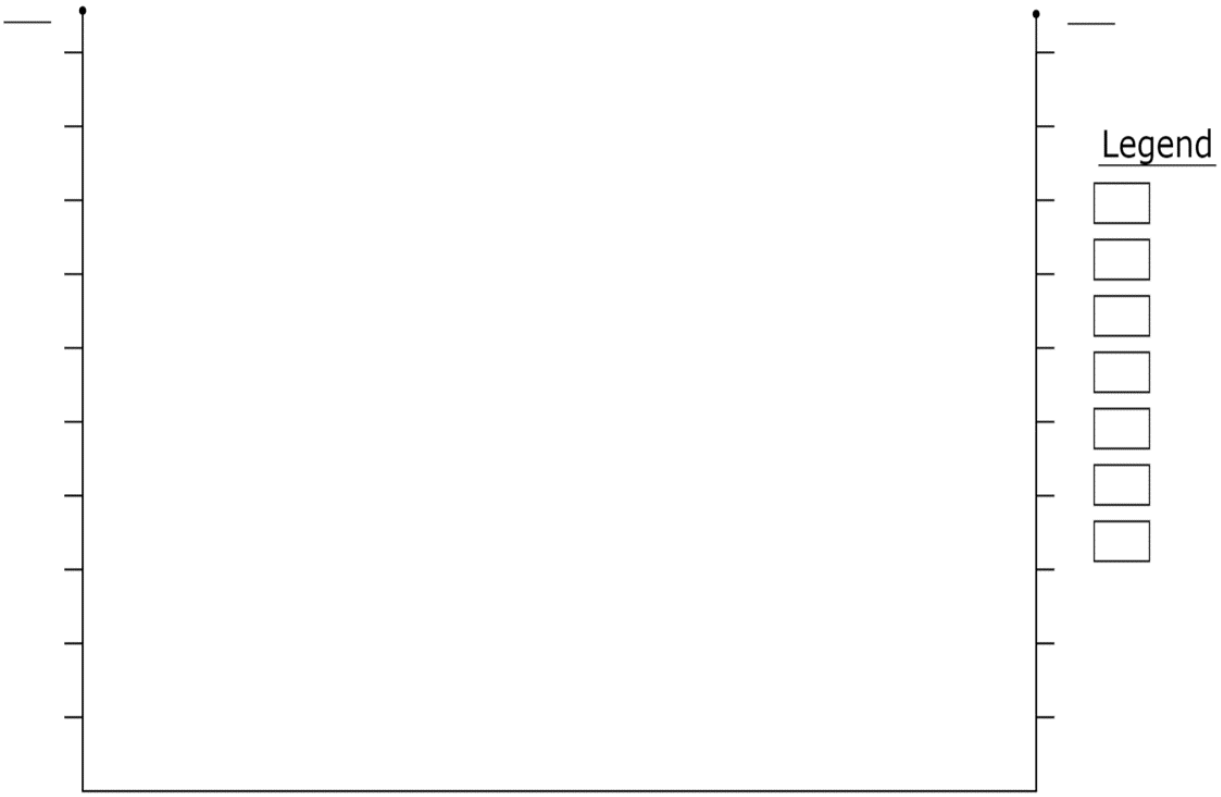


Figure 16.14: Figure for Questions 7-10, Activity 16D.

8. Using the cross-section you have prepared and the distances between the upper and lower contacts for each unit, calculate the thickness of the following units. Mark the location where you measured your thicknesses with a line on your cross-section. *Note: the thickness is the shortest distance between the upper and lower contact of a bed: a line that runs perpendicular to both contacts.*

- **a.** Limestone:
- **b.** Sandstone:
- **c.** Mudstone 2:
- **d.** Chalk:
- **e.** Conglomerate:

9. Why can't you measure the thickness of the shale or mudstone 1 units?

10. Describe the geological history of the map area, a bulleted list is OK to use here. *Hint: start with the oldest event and describe events as they occurred up to the present day.*

Attributions

- Figure 16.13: Derivative of “Murky Mists Mountain” (CC-BY 4.0; Karla Panchuk via OpenPress) by Chloe Branciforte
- Figure 16.14: Derivative of “Murky Mists Mountain Cross-Section Template” (CC-BY 4.0; Karla Panchuk via OpenPress) by Chloe Branciforte

Activity 16E: Delightful Dells Geological Paradise Geologic Map

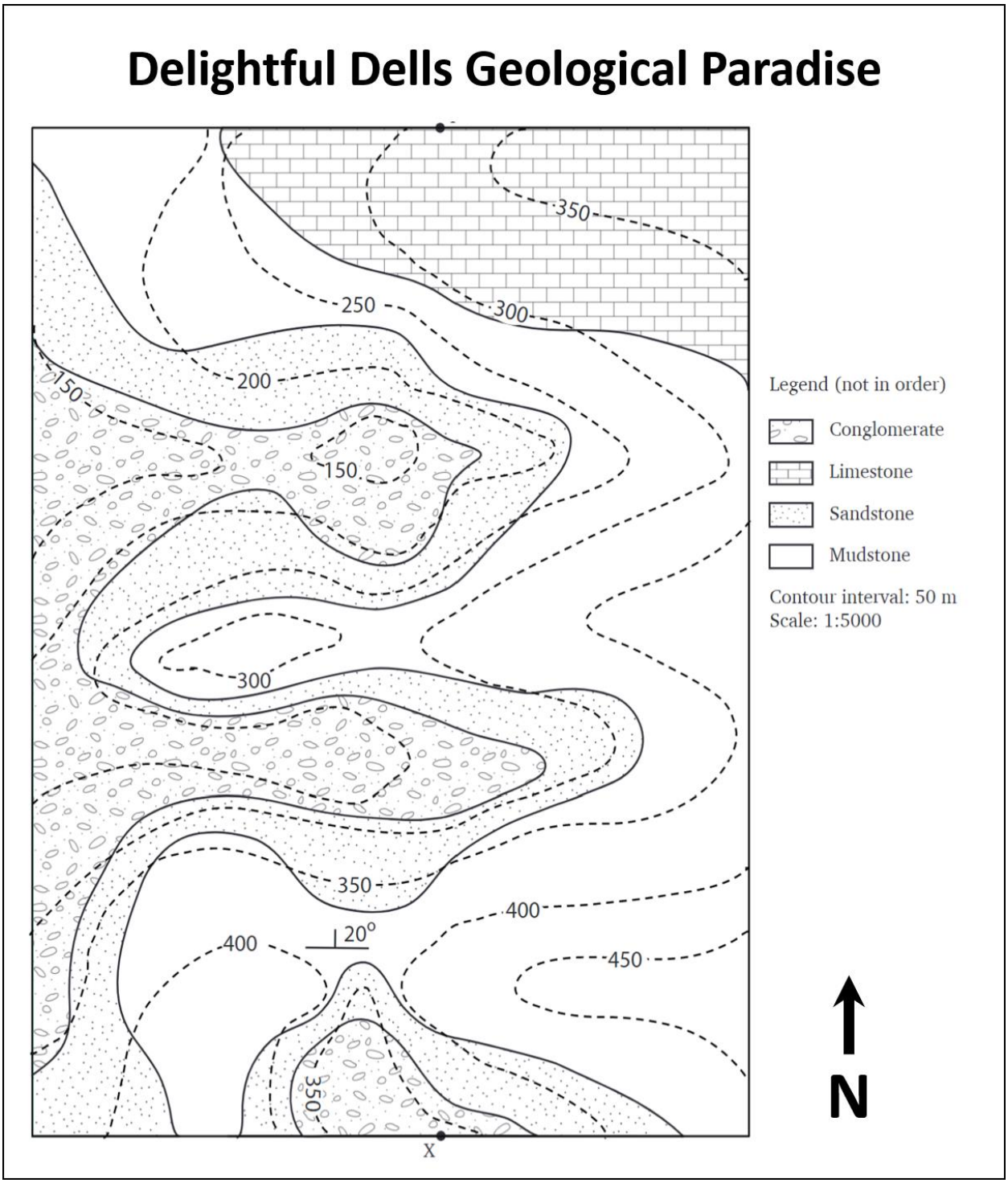


Figure 16.15: Figure for Questions 1-6, Activity 16E.

1. Examine the map of the Delightful Dells Geological Paradise. Refer to the map legend. What kind of rocks are found in this map area (circle all that apply)?
    a. Sedimentary
    b. Igneous
    c. Metamorphic

2. How many units can you see?

3. Draw a geological cross-section between the points X and Y indicated on this map. *Note: you will have to prepare a cross-section from scratch for this exercise, but you can use the format from the Murky Mists cross-section as a guide. This is a more challenging cross-section and you may have to make several changes to get it right. Make sure you have an eraser with you!*

4. Using the cross-section you have prepared and the distances between the upper and lower contacts for each unit, calculate the thickness of the following units. Mark the location where you measured your thicknesses with a line on your cross-section. *Note: the thickness is the shortest distance between the upper and lower contact of a bed: a line that runs perpendicular to both contacts.*
    a. Mudstone:
    b. Sandstone:

5. Why can't you measure the thickness of the conglomerate or the limestone?

6. Describe the geological history of the map area, a bulleted list is OK to use here. *Hint: start with the oldest event and describe events as they occurred up to the present day.*

Attributions

- Figure 16.15: Derivative of “Delightful Dells Geological Paradise” (CC-BY 4.0; Karla Panchuk via OpenPress) by Chloe Branciforte

Activity 16F: Four-River Ridge Geologic Map

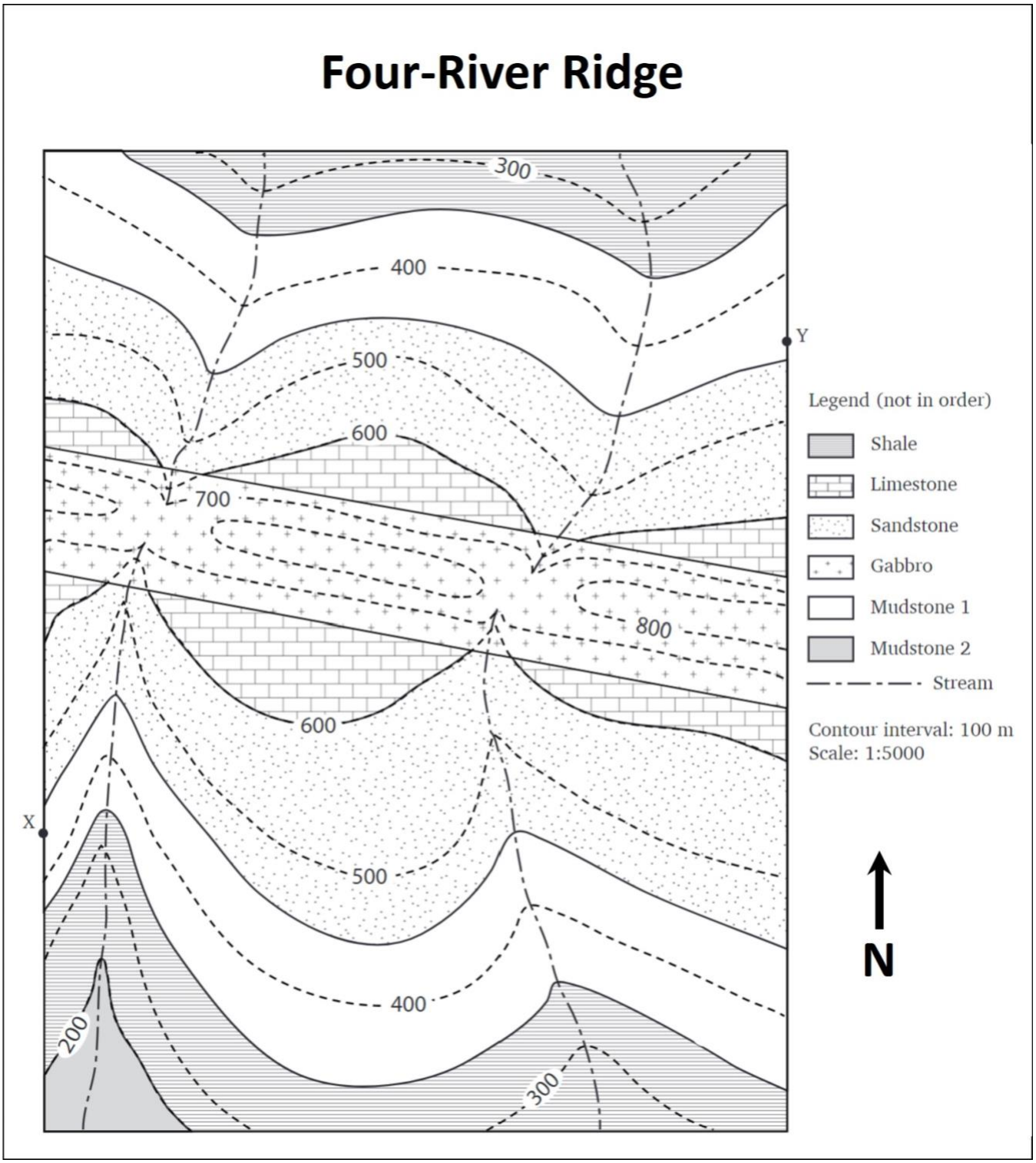


Figure 16.16: Figure for Questions 1-8, Activity 16F.

1. Examine the map of the Four-River Ridge. Refer to the map legend. What kind of rocks are found in this map area (circle all that apply)?
    a. Sedimentary
    b. Igneous
    c. Metamorphic

2. How many units can you see?

3. Carefully study the relationship between the contour lines and the contact between the limestone and sandstone. What does this tell you about the orientation of these beds?

4. Examine the gabbro unit. What V pattern is formed by the four rivers that cut through this unit? What does this tell you about the orientation of this unit?

5. What is the strike and dip of the sedimentary units in this map area?
    a. Strike direction:
    b. Dip direction:

6. What is the strike and dip of the gabbro dyke?
    a. Strike direction:
    b. Dip direction:

7. Draw a geological cross-section between the points X and Y indicated on this map. *Note: you will have to prepare a cross-section from scratch for this exercise, but you can use the format from the Murky Mists cross-section as a guide.*

8. Describe the geological history of the map area, a bulleted list is OK to use here. *Hint: start with the oldest event and describe events as they occurred up to the present day.*

Attributions

- Figure 16.16: Derivative of “Four-River Ridge” (CC-BY 4.0; Karla Panchuk via OpenPress) by Chloe Branciforte

Activity 16G: Geologic Map of Yosemite Valley

Visit the National Geologic Map Database and download the PDF version of **Bedrock Geologic Map to Yosemite Valley (1985) by Frank Calkins** (or ask your instructor if paper copies are available). Calkins did most of this mapping in the 1920s and his work was posthumously published by the USGS. Behold! This is one of the most famous maps in **igneous petrology** (the study of the chemistry and evolution of igneous rock and magma). We will use it to practice geologic and topographic map reading.

Part 1 - The Basics: This series of questions are designed to understand the basic geology and topography of the map.

1. What is the **map scale**?

2. What is the map's **contour interval**?

3. What is the map's **INDEX contour interval**?

4. What is the highest-elevation feature on the map? *Hint: It is a peak near the east side of the map*.
    a. What is its elevation?

5. Where is the lowest-elevation feature on the map? *Hint: Yosemite Valley is a…wait for it…VALLEY! And…what feature is typically positioned in the bottom of VALLEYS? Where are these features at their lowest elevation?*

    a. What is its elevation at its lowest point?

6. Which is higher elevation, El Capitan or Half Dome?

7. What are the coordinates of the map's northeast corner?

    a. Latitude:

    b. Longitude:

8. What are the coordinates of the summit of El Capitan?

    a. Latitude:

    b. Longitude:

9. What is the YOUNGEST rock?

    a. What is the Geologic Age?

    b. Where is it found?

10. What is the OLDEST rock?

    a. What is the Geologic Age?

    b. Where is it found?

11. What family of rocks is almost the entire map area made of?

12. What Earth material covers almost the entire floor of Yosemite Valley?

Part 2 - Igneous Geology: Let's review some concepts related to igneous processes. They do not involve the map. For a good discussion of igneous rocks, review the igneous chapter.

13. What is the difference between an **intrusive** and **extrusive** igneous rock?

Recall that igneous rocks are chemically classified by the amount of SiO_2 in their minerals. This is the classic mafic to felsic scale.

14. What VOLCANIC (extrusive) rocks have the following compositions?

Mafic:
Intermediate:
Felsic:

15. What PLUTONIC (intrusive) rocks have the following compositions?

Mafic:
Intermediate:
Felsic:

16. What tectonic settings typically form the following compositions? *Hint: This question is challenging, look back at the igneous and volcanoes chapter for help.*

Mafic:
Intermediate:
Felsic:

Part 3 - Analysis: Okay, geologists: get ready to apply this all to the real world.

Let's explore what made the igneous rocks of Yosemite Valley. This will tell us something interesting about the geologic history of the Sierra Nevada.

17. What kind of intrusive igneous rock is most of the rocks in Yosemite Valley? Be specific.

a. What is its composition (mafic, intermediate, felsic)?

b. WHERE are such magmas formed?

c. Again…how old are all of these rocks?

d. What is this all evidence of? What was happening in this part of the Sierra and when? Please include all of the elements in questions 17a-d. Use at least TWO sentences. *DO NOT Google*.

18. Let's explore the erosive history of the Sierra Nevada. Erosion rates are a very important thing to quantify when you are thinking about the geologic history of a region. According to K-Ar thermobarometry, most of the granitic rocks of the Sierra were emplaced at a depth of 10 km. We are going to figure out how high it has uplifted.

a. According to the map, how high above sea level is Half Dome today?

b. Those units are in feet. Convert it to miles. *Show your work.*

c. Remember, the rock of Half Dome was formed 10 km below the surface of Earth. Convert 10 km to miles. *Show your work.*

d. The total distance Half Dome has uplifted is roughly equal to its height above sea level added to the depth at which it was formed. Add together 18b and 18c.

e. When uplift of the region began is the subject of much debate. Let's assume that it began uplifting about when central California shifted from a convergent to a transform boundary (~30 Ma). What is the **rate** at which the Central Sierra has uplifted? *Hint: Rate=distance/time*; *use the units mi/Ma. Show your work.*

f. The units mi/Ma is clunky and difficult to make sense of. Convert this unit to mi/year. *Show your work.*

g. That number is TINY! Or is it? Convert that number to inches/year. Your answer should be less than 1 in/year but larger than 0.001 in/year. *Show your work.*

Woah, that's fast! This number represents how rapidly the Sierras have uplifted.

Different rocks weather at different rates: those that weather slowly form large cliffs and those that weather quickly are reduced to rubble. This is one of the reasons why Yosemite has such tall cliffs; they are all made of granite, a resilient rock. However, minor differences in granitic rock chemistry will have an effect on weathering rates. To explore this, we will measure the gradient of two different rocks of different compositions.

19. What is the most mafic formation that has significant exposure? *Hint: read the key; it occasionally appears as a hornblende gabbro.*

20. What is the most felsic formation in the region? *Hint: it rarely contains biotite.*

21. Let's find an area where they contact each other so we can compare their gradients. Find this region on your map:

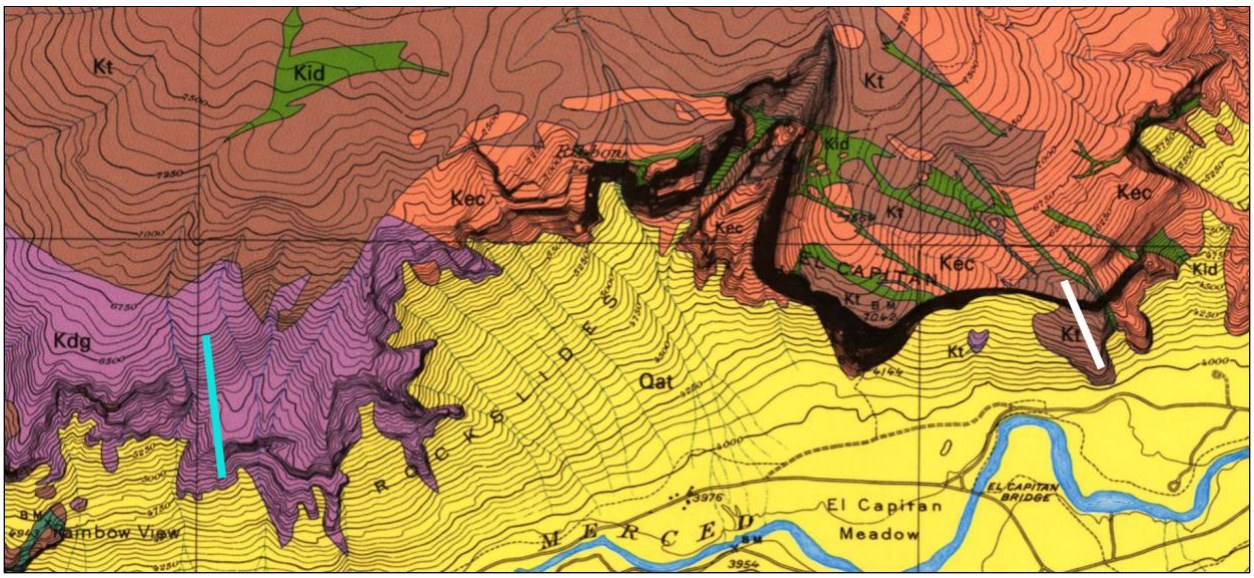


Figure 16.17: Section of the Geologic Map to use for Question 21, Activity 16G.

a. Determine the gradient (feet/mile) of the Taft Granite (white line). Use the graphic scale on the main map to evaluate your distance (use miles). Use the topo lines to evaluate change in elevation (use feet). *Hint: Gradient= change in elevation/distance. Show your work.*

Gradient of Taft Granite:

b. Determine the gradient (feet/mile) of the Rockslides (turquoise line). Use the graphic scale on the main map to evaluate your distance (use miles). Use the topo lines to evaluate change in elevation (use feet). *Hint: Gradient= change in elevation/distance. Show your work.*

Gradient of Diorite of the Rockslides:

c. According to your data, which igneous composition is more susceptible to weathering? Mafic or felsic?

Let's look at some patterns in the granitic rocks.

22. What is the pattern in geologic ages? What happens as you move from west to east?

This happens because of the angle of subduction. The steeper the slab is subducting, the closer to the continental margin the intrusive activity will be (see figure).

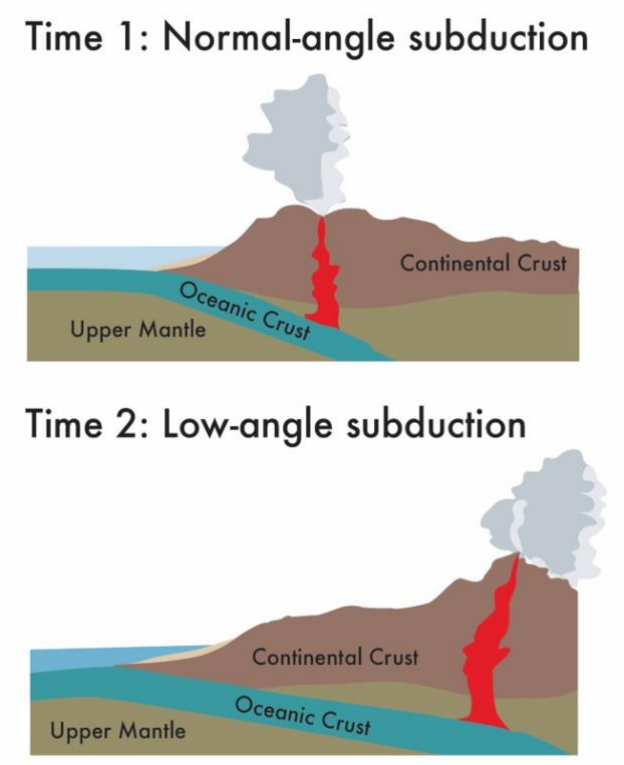


Figure 16.18: Figure to use for Question 23, Activity 16G.

23. Subduction angle is controlled by a variety of things, one of which is subduction rate. The faster the subduction, the steeper the angle. Over time during the Cretaceous, what was happening to subduction rates (i.e. were they increasing or decreasing)?

Attributions

- Figure 16.17: Derivative of “Bedrock Geologic Map of Yosemite Valley, Yosemite National Park, California” (Public Domain; Frank C. Calkins/USGS) by Chloe Branciforte
- Figure 16.18: “Subduction Angles” (CC-BY 4.0; Emily Haddad, own work)

Chapter 17: Coastal Processes and Landforms

Learning Outcomes

After completing this chapter, you should be able to:

- ✓ Identify the submergent coastlines in the US and common depositional features, including beaches, spits and hooks, tombolos, and barrier islands.
- ✓ Identify emergent coastlines in the US and common erosional features, including sea stacks, arches, cliffs, terraces and wave-cut platforms.

Thumbnail for Chapter 17:

Thumbnail: Derivative of "Point Arena-Stornetta unit of the California Coastal National Monument" (Public Domain; Bob Wick/BLM via Flickr) by Chloe Branciforte

Our Oceans

Figure 17.1: Doldrums in the Pacific Ocean.

Oceans cover 71% of Earth's surface and hold 97% of Earth's water, yet nearly 95% of that ocean is completely unexplored. The entire ocean floor has been mapped, but only to a resolution of 3 miles: this means that we can only see features larger than 3 miles wide. We have better maps of the surface of Mars and the moon than we do the bottom of the ocean. We know very, very little about most of the ocean, particularly for the middle and deeper parts far away from the coasts. Why? It is a challenging place to work! In many ways, it is easier to put a person into space than it is to send a person down to the bottom of the ocean. It is dark, cold, and the pressure exerted by the water above is enormous, equivalent to one person trying to support 50 jumbo jets. However, the water that the oceans contain is critical to plate tectonics, volcanism, and of course, life on Earth. The ocean floor is covered with an average of 13,000 feet of water and is pitch black below a few thousand feet or so; it is not easy to discover what is down there. We know a lot more about the oceans than we used to, but there is still a great deal more to discover.

Earth has had oceans for a very long time, dating back to the point where the surface had cooled enough to allow liquid water to condensate, only a few hundred million years after Earth's formation. At that time there were no continental rocks, so Earth's water was likely spread out over the surface in one giant (but relatively shallow) ocean.

A person who studies the oceans and coastal processes may have many titles including oceanographer, coastal geomorphologist, sedimentologist, or climate scientist. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways include environmental policy and legislation and consulting, via the private sector or state and federal agencies. Many of these career options require a college degree and postgraduate work. If this pathway is of interest to you, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible. Also, visit National Parks, CA State Parks, museums, gem

& mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 17.1: “Doldrums of the Pacific” (CC-BY 4.0; Chloe Branciforte, own work)

Topography of the Sea Floor

We examined the topography of the sea floor from the perspective of plate tectonics and in sedimentary rocks but here we are going to take another look at **bathymetry** from an oceanographic perspective. The topography of the oceans is shown in **Figure 17.2**. Notice the variety of blue colors: light blue indicates shallow ocean water whereas darker blues indicate deeper ocean waters.

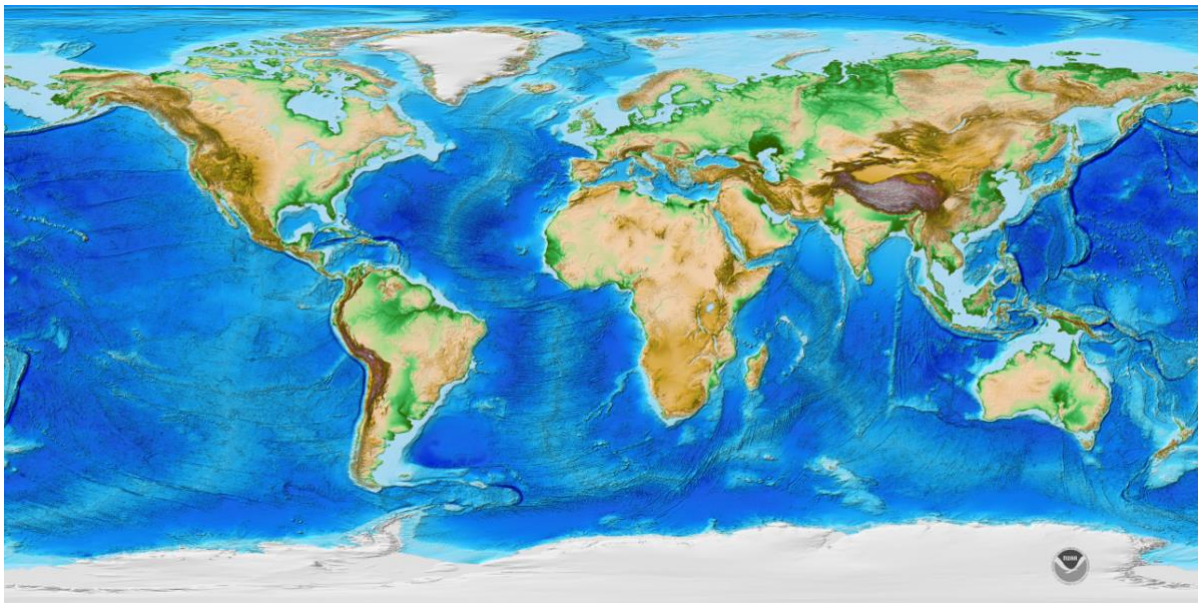


Figure 17.2: Color shaded-relief image of the continents and oceans.

A topographic profile of the Pacific Ocean floor between Japan and the Pacific Northwest is shown in **Figure 17.3**. This diagram has a significant amount of vertical exaggeration (the vertical scale overemphasizes the height of the features relative to their width), but it captures the varied topography of the seafloor well. From the deepest trenches (up to 7 miles deep at the Mariana Trench) to the highest mountains (Mauna Kea on the Big Island of Hawaii is taller than Mount Everest, when measured from its base to its summit), the floor of the Pacific is not the flat basin we once envisioned. The vast sediment-covered **abyssal plains** of the oceans, however, *are* much flatter than any similar-sized areas on the continents and cover more than 50% of the Earth's surface (**Figure 17.4**). These extremely deep (over 10,000 feet) and flat areas of the sea-floor are interrupted by massive underwater mountain chains, **seamounts**, or **MORs** (**Figure 17.3**). Other major topographic features in the oceans include the continental shelves, slopes, and rises that surround the continental crust.

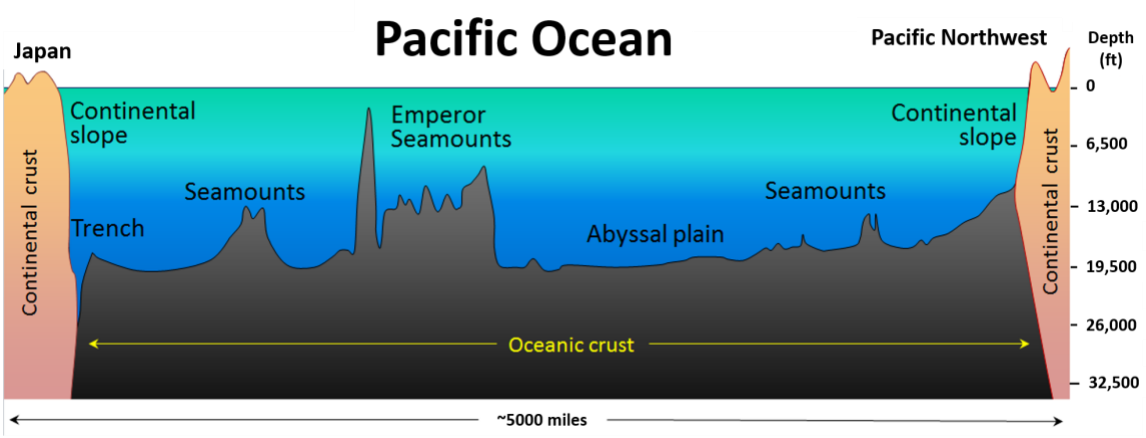


Figure 17.3: The generalized topography of the Pacific Ocean sea floor between Japan and the Pacific Northwest.

Starting from land, a trip across an ocean basin along the seafloor would begin with crossing the **continental shelf** (**Figure 17.4**). The continental shelf is an area of relatively shallow water, usually less than a few hundred feet deep, that surrounds a continent. It is narrow or nearly nonexistent in some places; in others, it can extend for hundreds of miles. On the East and Gulf Coasts, where there are **passive margins** (no plate boundaries), the continental shelf averages around 85 miles wide. On the West Coast, where there is an **active margin**, the shelf is less than half as wide. Due to the abundance of light and nutrients from upwelling and runoff, the waters along the continental shelf are usually biologically productive.

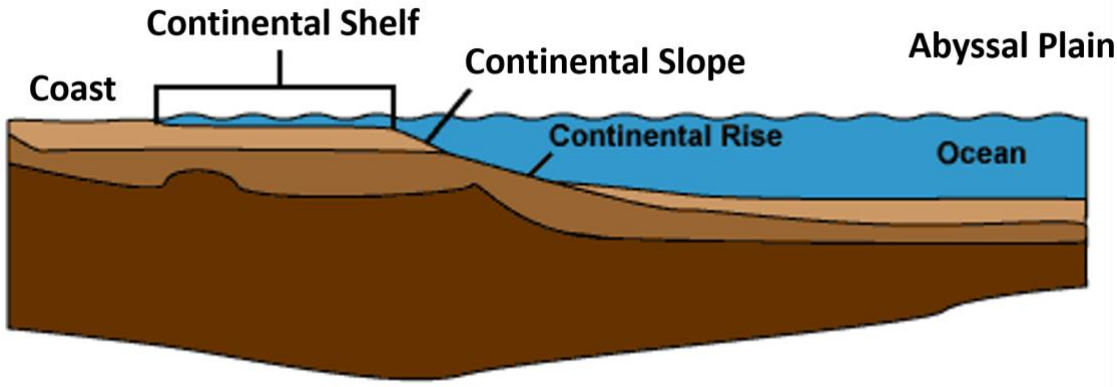


Figure 17.4: A generalized cross-section from the coast out to the abyssal plain.

At the edge of the shelf is the boundary known as the **continental slope**, which separates the shelf from the **continental rise** (**Figure 17.4**). The continental rise is very slightly angled, between 0.5 degrees and 1.0 degrees. Deposition of sediments at the mouth of submarine canyons carved into the shelf and slope may form enormous fan-shaped accumulations called **submarine fans** on both the continental slope and continental rise.

Attributions

- Figure 17.2: “ETOPO1 1 Arc-Minute Global Relief Model” (Public Domain; C. Amante and B.W. Eakins via NOAA)
- Figure 17.3: “Generalized Topography of the Pacific Ocean” (CC-BY 4.0; Steven Earle via OpenText)
- Figure 17.4: Derivative of “Continental Shelf” (Public Domain; Interiot via Wikimedia Commons) by Chloe Branciforte

Waves

Waves form on the ocean and on lakes because energy from wind is transferred to the water. The stronger the wind, the longer it blows; the larger the area of water over which it blows, referred to as the wind's **fetch**, the larger the waves are likely to be. The important parameters of a wave are 1) its **wavelength**, the horizontal distance between two crests or two troughs, 2) its **amplitude**, the vertical distance between a trough and a crest, and 3) its **velocity**, the speed at which wave crests move across the water. (**Figure 17.5**).

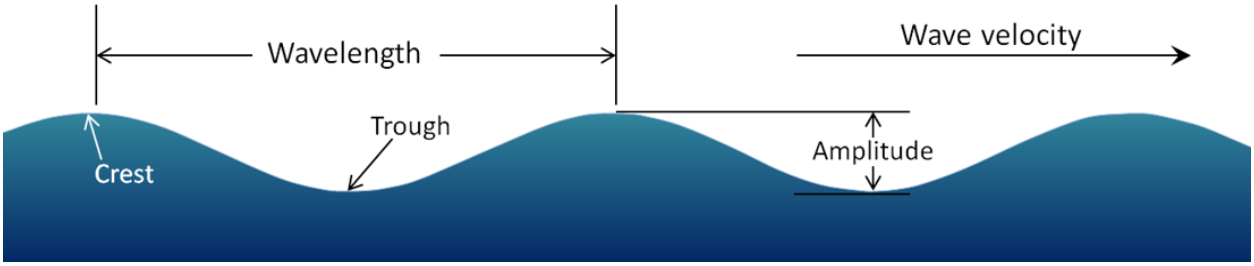


Figure 17.5: The parameters of water waves.

As a wave moves across the surface of the water, the water itself mostly just moves up and down and only moves a small amount in the direction of wave motion. As this happens, a point on the water surface circumscribes a circle with a diameter that is equal to the wave amplitude (**Figure 17.6**). This motion is also transmitted to the water underneath, and the water is disturbed by a wave to a depth of approximately one-half of the wavelength. Wave motion is illustrated quite clearly on the **Wikipedia "Wind wave" site**. If you look carefully at that animation and focus on the small white dots in the water, you should be able to see how the amount that they move decreases with depth.

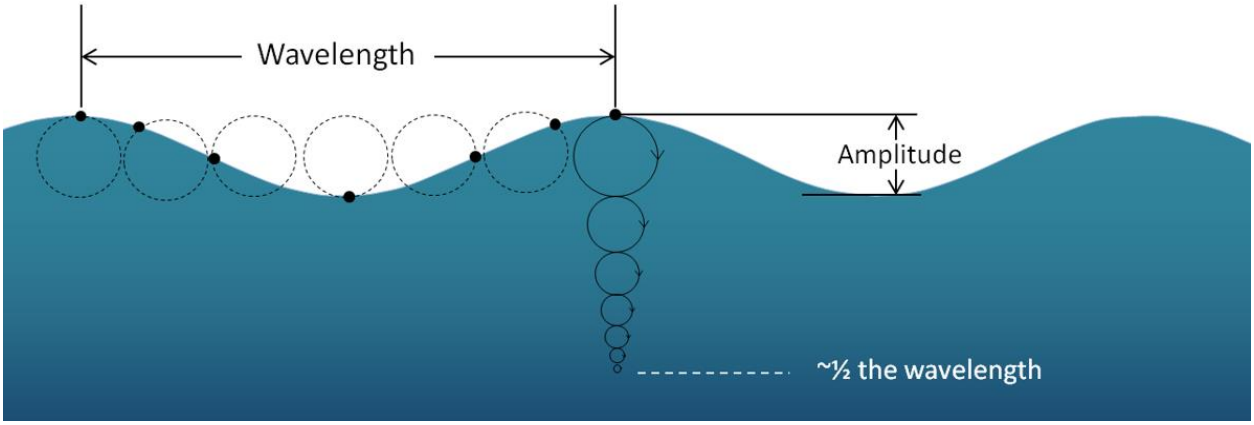


Figure 17.6: The orbital motion of a parcel of water (black dot) as a wave moves across the surface.

The one-half wavelength depth of disturbance of the water beneath a wave is known as the **wave base**. Since ocean waves rarely have wavelengths greater than 650 feet, and the open ocean is several thousand feet deep, the wave base does not normally interact with the bottom of the ocean. However, as waves approach the much shallower water near the shore, they start to "feel" the bottom and are affected by this interaction. The wave "orbits" are both flattened and slowed by dragging, with the implication that the wave amplitude (height) increases and the wavelength decreases (the waves become much steeper). The ultimate result of this is that the waves lean forward, and eventually break.

Waves normally approach the shore at an angle, which means that one part of the wave feels the bottom sooner than the rest of it; the part that feels the bottom first will slow down first. Even though they bend and become nearly parallel to shore, most waves still reach the shore at a small angle, and as each one arrives, it pushes water along the shore, creating what is known as a **longshore current** within the surf zone. Another important effect of waves reaching the shore at an angle is that when they wash up onto the beach, they do so at an angle, but when that same wave water flows back down the beach, it moves straight down the slope of the beach. The upward-moving water, known as the **swash**, pushes sediment particles along the beach, while the downward-moving water, the backwash, brings them straight back. With every wave that washes up and then down the beach, particles of sediment are moved along the beach in a zigzag pattern. The combined effects of sediment transport within the surf zone by the longshore current and sediment movement along the beach by swash and backwash is known as longshore drift (**Figure 17.7**). **Longshore drift** moves a tremendous amount of sediment along coasts of oceans and large lakes around the world and it is responsible for creating a variety of depositional features.

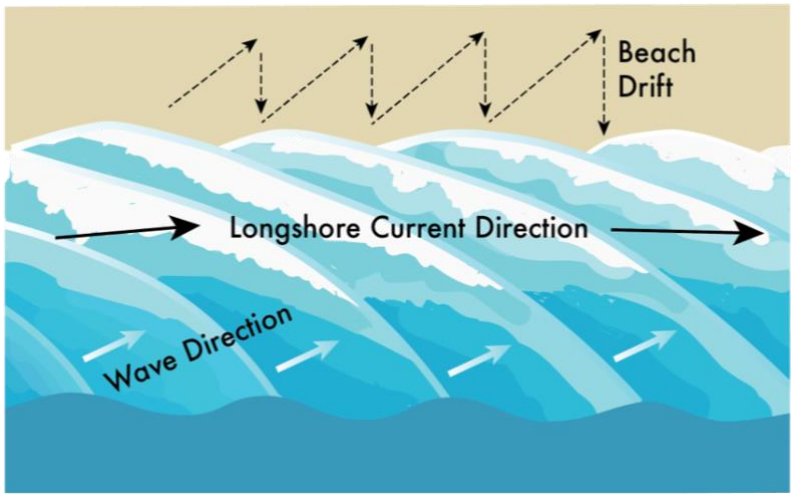


Figure 17.7: The longshore current moves sediment down the beach.

A **rip current** is another type of current that develops in the nearshore area and has the effect of returning water that has been pushed up to the shore by incoming waves. Rip currents flow straight out from the shore and are fed by the longshore currents. They die out quickly just outside the surf zone but can be dangerous to swimmers who get caught in them. If part of a beach does not have a strong unidirectional longshore current, the rip currents may be fed by longshore currents going in both directions.

Tides are very long-wavelength but low-amplitude waves on the ocean surface that are caused by variations in the gravitational effects of the Sun and Moon. Tide amplitudes in shoreline areas vary quite dramatically from place to place. As the tides rise and fall they push and pull a large volume of water in and out of bays and inlets and around islands. They do not have as significant an impact on coastal erosion and deposition as wind waves do, but they have an important influence on the formation of features within the **intertidal zone**.

Attributions

- Figure 17.5: “The Parameters of Water Waves” (CC-BY 4.0; Steven Earle via OpenText)
- Figure 17.6: “Wave Motion” (CC-BY 4.0; Steven Earle via OpenText)
- Figure 17.7: “Longshore Current” (CC-BY 4.0; Emily Haddad, own work)

Erosional and Depositional Landforms

Some coastal areas are dominated by erosion, like California and the rest of the US Pacific Coast; other coastlines are dominated by deposition, like the Atlantic and Gulf Coasts (**Figure 17.8**). On almost all coasts, however, both deposition and erosion are happening to varying degrees in different places. For this introductory course, we will oversimplify the North American coastlines to illustrate basic concepts: the West Coast is emergent and therefore erosional, while the East and Gulf Coasts are submergent and therefore depositional. The real world is obviously more complex, and it is possible to find all landforms on both coastlines.

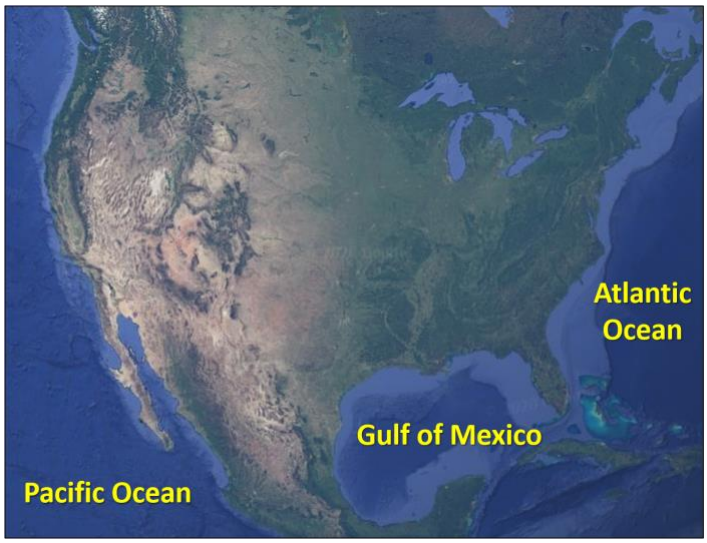


Figure 17.8: The Pacific Ocean is off the West Coast of North America, whereas the Atlantic Ocean is off the East Coast. The Gulf of Mexico is to the southeast.

Erosional Landforms

A key factor in determining if a coast is dominated by erosion or deposition is its history of tectonic activity. An **emergent coastline** has been exposed by the relative fall in sea level by either **isostasy**, **eustasy**, or tectonic uplift. In general, California's coastline is relatively active tectonically; uplift for tens of millions of years has resulted in a local "fall" in sea-level. Our emergent coastlines are typically dominated by erosional features, with rocky shores, narrow beaches and continental shelves.

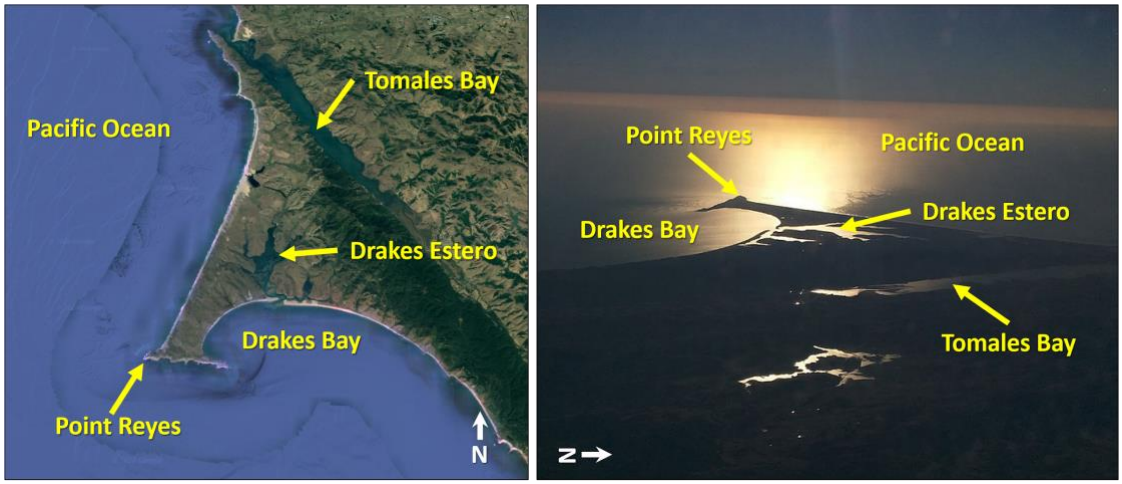


Figure 17.9: Point Reyes, a headland, and Drakes Bay, northwest of San Francisco.

Several unique erosional features commonly form on these rocky shores. When waves approach an irregular shore, they are slowed down to varying degrees, depending on differences in the water depth, and as they slow, they are bent or refracted. Because of refraction, the energy of the waves, which moves perpendicular to the wave crests, is focused on the **headlands** (**Figure 17.9**).

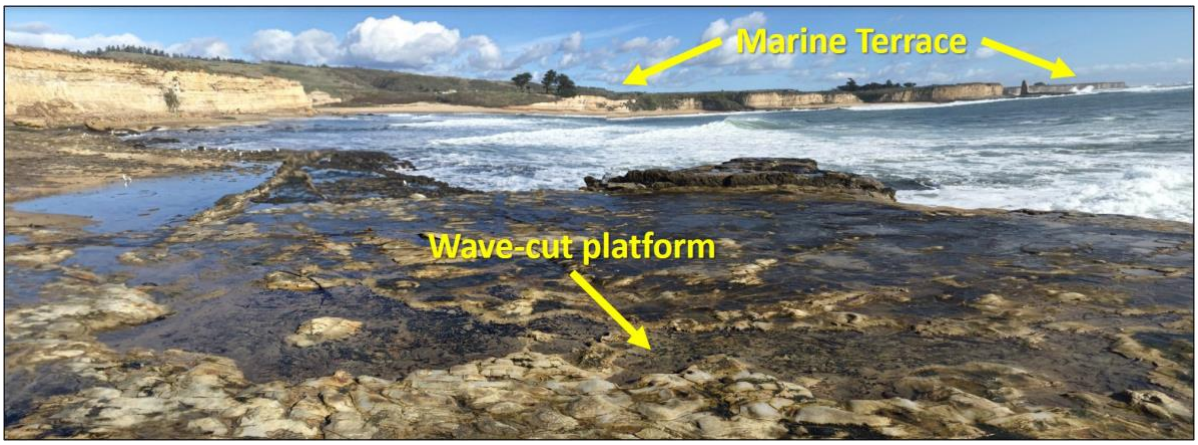


Figure 17.10: Marine terraces and wave-cut platforms in northern California.

Wave erosion is greatest in the **surf zone**, where the wave base strongly affects the seafloor and waves break. The result is a narrow flat surface known as a **wave-cut platform** or **wave-cut terrace**, found at the base of a sea cliff or along the shoreline (**Figure 17.10**). Read more about marine terraces from the USGS - Fact Sheet, Landscapes from the Waves - Marine Terraces of California.

More resistant rock that does not erode completely during the formation of a wave-cut platform often remains behind to form a **sea stack**. These sea stacks are typically steep, vertical columns of rock formed over time. **Sea arches** and **sea caves**, the results of sequential erosion of promontories and headlands, may eventually collapse and form stacks (**Figure 17.11**).

Figure 17.11: Point Arena-Stornetta situated along the rugged Mendocino County coastline in northern California.

Depositional Landforms

Recall that emergent coastlines result from a relative fall in sea level. Accordingly, a **submergent coastline** has been covered or inundated by the sea as a result of a relative rise in sea level from either **isostasy** or **eustasy**. The US Atlantic and Gulf Coasts are passive margins and have not seen much tectonic activity during the last hundred million years. Generally, submergent coastlines are dominated by deposition, although erosion will still occur, and are characterized by sandy beaches and wide continental shelves.

The evolution of sandy depositional features on seacoasts is primarily influenced by waves and currents, especially **longshore currents**. As sediment is transported along a shore, it is either deposited on **beaches**, or creates another depositional feature. A **beach** is a landform along a body of water that consists of loose sediments, which range in size and composition but are typically derived from the local bedrock, shells or coral. A **spit**, is an elongated sandy deposit, similar to a beach, that extends out into open water in the direction of a longshore current (**Figure 17.12**). Should the spit begin to grow backwards and curve, it is referred to as a **hook**. A spit that extends across a bay to the extent of closing, or almost closing it off, is known as a **baymouth bar**. Most bays have rivers flowing into them, and since this water must get out, it is rare that a baymouth bar will completely close the entrance to a bay. In areas with near-shore islands and sufficient sediment transport, a **tombolo** and **tied-island** may develop. In areas where coastal sediments are abundant and coastal relief is low, it is also common for **barrier islands** to develop. These islands are composed entirely of sand and have a distinct elongated shape; typically they develop only a few miles from the mainland (**Figure 17.12**).

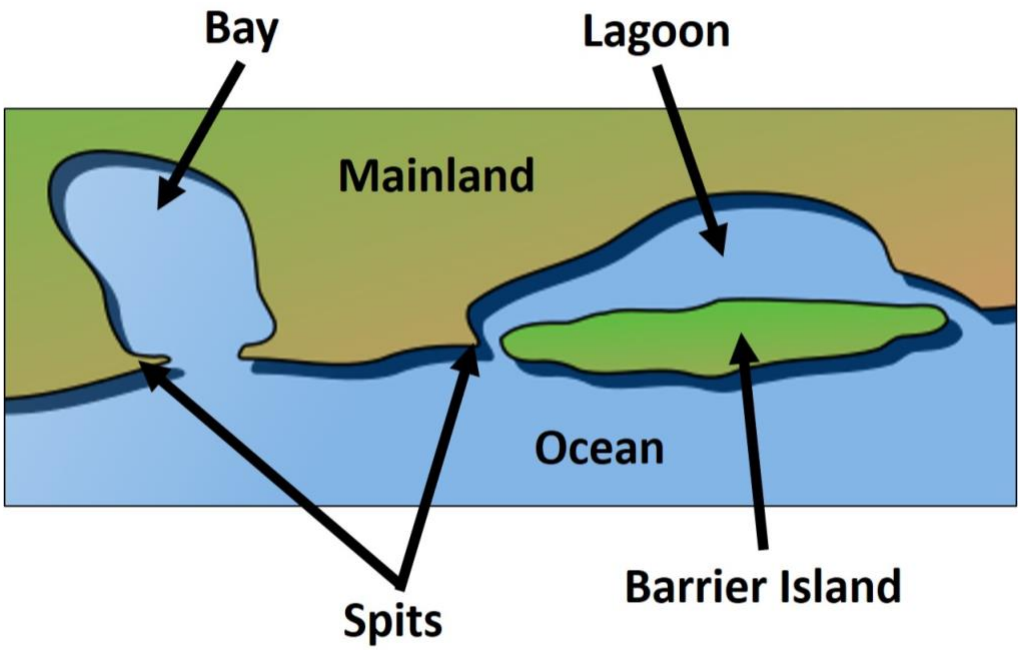


Figure 17.12: Depositional coastal landforms.

Attributions

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- Figure 17.9: Derivative of “Point Reyes and Drakes Bay” (CC-BY-SA 4.0; DickLyon via Wikimedia Commons) by Chloe Branciforte and Google Earth
- Figure 17.10: “Marine Terrace and Platform” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)
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- Figure 17.12: Derivative of “Accreting Coast Image6” (Public Domain; Surachit via Wikipedia)

Human Interface with Shorelines

There are various modifications that we make to influence shoreline processes for our own purposes. Sometimes these changes are effective and appear to be beneficial, although in most cases there are unintended negative consequences that we do not recognize until much later.

Occasionally beaches are armored with **riprap** and concrete blocks to limit the natural erosion that threatens the properties at the shore (**Figure 17.13**). The unintended effect of this installation will be to deprive the area of sediment. If the armor remains in place for several decades, there is a significant risk that the depositional landforms will start to erode. This could also affect the biology of the area, including many of the organisms that use that area as their habitat, and people who use the area for recreation.

Figure 17.13: In February 2017, large boulders were installed as rip-rap to armor the shore against further erosion at Goleta Beach in Southern California.

Seawalls also limit erosion and can be useful amenities for the public; however, they too have geological and ecological costs. Seawalls affect the behavior of waves and longshore currents, sometimes with negative results. When a shoreline is "hardened" in this way, important marine habitat is lost and sediment production is reduced, which can affect beaches elsewhere.

Breakwaters are structures that run parallel to the shore (**Figure 17.14**). Typically, these have acted as islands and sand is deposited in the low-energy water behind them, similar to how a tombolo may form. Negative impacts are not yet well understood but likely involve loss of marine animal habitat.

Groins are structures constructed perpendicular to the beach (**Figure 17.14**). They have an effect that is similar to breakwaters, while trapping sediment by slowing the longshore current.

Figure 17.14: Ventura Harbor has both breakwaters and groins present.

Most of the sediment that forms beaches along our coasts comes from rivers, so if we want to take care of beaches, we must take care of rivers. When a river is dammed, its sediment load is deposited in the resulting reservoir, and while the reservoir is filling up that sediment cannot get to the sea. During this time, beaches and other depositional landforms within miles of the river's mouth are at risk of erosion as longshore currents displace sediment that is not replenished by the river.

For more on our nation's changing coastlines, read this USGS Fact Sheet - Shoreline Change Research.

Attributions

- Figure 17.13: “Armoring the Shore at Goleta Beach” (Public Domain; Daniel Hoover via USGS)
- Figure 17.14: “Ventura Harbor” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)

Activity 17A: Identifying Coastal Landforms

1. In general, the West Coast of the US is an example of which type of coastline?
    a. Why?

2. In general, the East and Gulf Coasts of the US is an example of which type of coastline?
    a. Why?

3. Identify the landforms in **Figure 17.15** and their process of formation (deposition or erosion).
    a. Landform A:
    b. Landform B:
    c. These landforms typically develop due to which processes?

Figure 17.15: Landforms for Question 3 of Activity 17A.

4. Identify the landform in **Figure 17.16** and the process of formation (deposition or erosion).
    a. Landform C:
    b. This landform typically develops due to which processes?

Figure 17.16: Landform for Question 4 of Activity 17A.

5. Identify the landforms in **Figure 17.17** and their process of formation (deposition or erosion).
    a. Landform D:

    b. Landform E:

    c. These landforms typically develop due to which processes?

Figure 17.17: Landforms for Question 5 of Activity 17A.

6. Identify the landform in the image below and the process of formation (deposition or erosion).
    a. Landform F:
    b. This landform typically develops due to which processes?

Figure 17.18: Landform for Question 6 of Activity 17A.

7. Identify the landforms in the image below and their process of formation (deposition or erosion).
    a. Landform G:
    b. Landform H:
    c. These landforms typically develop due to which processes?

Figure 17.19: Landforms for Question 7 of Activity 17A.

8. Identify the landform in the image below and the process of formation (deposition or erosion).
    a. Landform I:
    b. This landform typically develops due to which processes?

Figure 17.20: Landform for Question 8 of Activity 17A.

Attributions

- Figure 17.15: Derivative of “Point Arena-Stornetta unit of the California Coastal National Monument” (Public Domain; Bob Wick/BLM via Flickr) by Chloe Branciforte
- Figure 17.16: Derivative of “California Coastal National Monument at Trinidad Head” (Public Domain; Bob Wick/BLM via Flickr) by Chloe Branciforte
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- Figure 17.19: “Coastal Landforms” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)
- Figure 17.20: “Lagoon” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)

Chapter 18: Desert Processes and Landforms

Learning Outcomes

After completing this chapter, you should be able to:

- ✓ Identify the broad categories of deserts.
- ✓ Identify common desert landforms.
- ✓ Describe the main types of sand dunes and the conditions that form them.

Thumbnail for Chapter 18:

Thumbnail: "Death Valley Dunes" (CC-BY 4.0; Emily Haddad, own work)

What Is a Desert?

About 30% of the land surface of the world is **arid** or **semi-arid**. This includes much of the polar regions, where little precipitation occurs and so are considered **polar deserts**. Deserts are typically classified by the amount of precipitation that falls (fewer than 10 inches), by the temperature that prevails, or by geographical location. While temperature extremes are often associated with deserts, they do not define them. Deserts exhibit extreme temperatures because of the lack of moisture in the atmosphere, including the low humidity and scarce cloud cover. Without cloud cover, the Earth's surface absorbs more of the Sun's energy during the day and emits more heat at night.

Figure 18.1: The Panamint Valley located in the northeastern reach of the Mojave Desert.

A person who studies the deserts and desert processes may have many titles including geomorphologist, sedimentologist or climate scientist. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways include environmental policy and legislation and consulting, via the private sector or state and federal agencies. Many of these career options require a college degree and postgraduate work. If this pathway is of interest to you, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible. Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 18.1: “Panamint Valley” (Public Domain; Jesse Pluim/BLM via Flickr)

How Do Deserts Develop?

Deserts are not randomly located on the Earth's surface, instead many deserts are gathered in distinct belts or regions. For example, sinking, dry air currents occurring at 30° North and South of the equator produce many of the most famous deserts including the Saharan Desert in Africa These areas are commonly referred to as **subtropical deserts** (**Figure 18.2**).

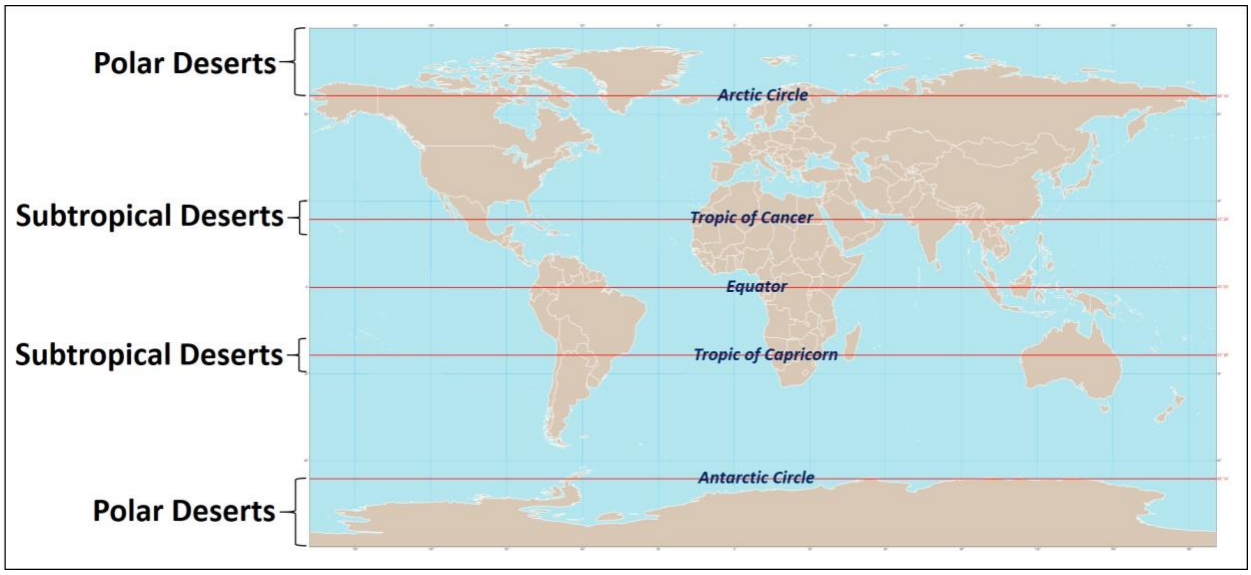

Figure 18.2: World map with major latitudes and desert types.

Subtropical deserts are the hottest deserts. In the US, the Chihuahuan, Sonoran, and Mojave are all examples of subtropical deserts (**Figure 18.3**). These deserts are often very hot and dry in the summer and cooler and dry in the winter. Rainfall does occur, but it short bursts, which may lead to **flash flooding**.

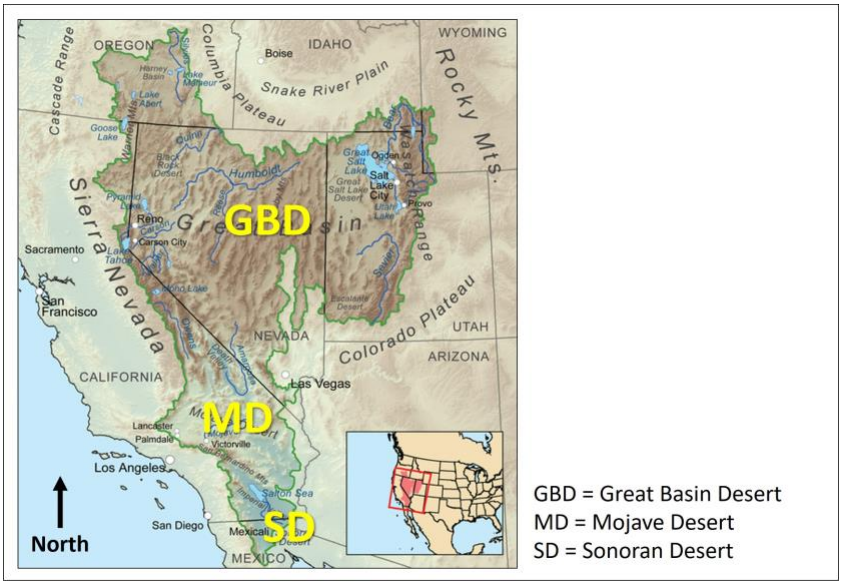

Figure 18.3: Major desert regions of the western US.

Dry areas located along a coast are referred to as **coastal deserts**. Coastal deserts typically occur in cool to warm areas along the west coasts of continents between 20° to 30° latitude and have cool winters and long, warm summers. Coastal winds blow in an

easterly pattern (from the interior of the continent) and prevent moisture from moving onto the land. Examples include the Namib Desert in Africa (**Figure 18.4**) and the Atacama Desert in Chile, the driest place on Earth.

Figure 18.4: Namib Desert meeting the Atlantic Ocean, an example of a coastal desert.

Other deserts can be found in the **rain shadow** created from prevailing winds blowing over mountain ranges (**Figure 18.5**). As the wind drives air up and over mountains, atmospheric moisture is released as snow or rain. Atmospheric pressure is lower at higher elevations, causing the moisture-laden air to cool. Cool air holds less moisture than hot air, and precipitation occurs as the wind rises up the mountain. After releasing its moisture on the windward side of the mountain, the dry air descends on the leeward or downwind side of the mountains to create an arid region with little precipitation called a rain shadow. Most rain shadow deserts in the western United States, including the Great Basin Desert, are due to the Sierra Nevada and Cascade ranges (**Figure 18.3**).

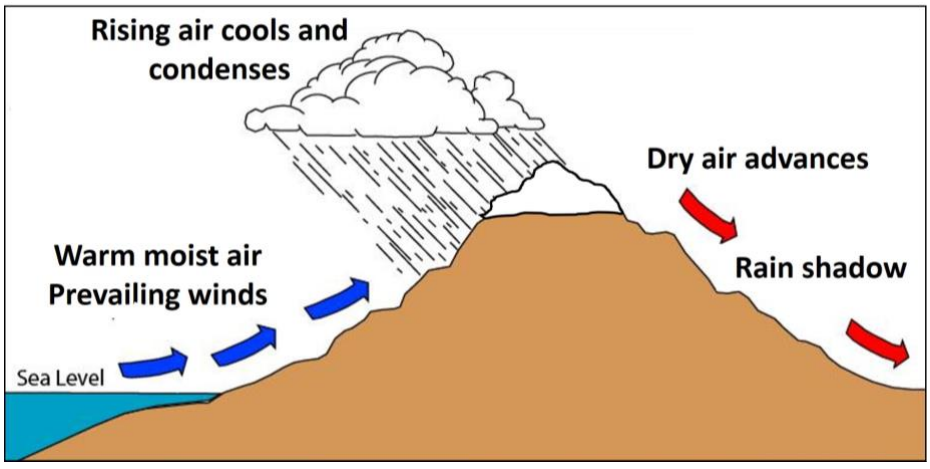

Figure 18.5: Orographic lift produces rain-shadow deserts.

Finally, **polar deserts**, like the vast areas of the Antarctic (**Figure 18.6**) and the Arctic, are created from sinking air that is too cold to hold much moisture. Although they are covered with ice and snow, these deserts have very low average annual precipitation. Consequently, Antarctica is Earth's driest continent.

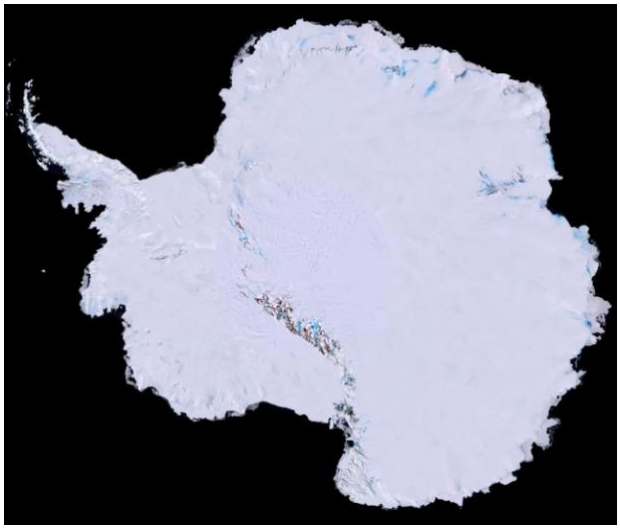

Figure 18.6: Antarctica is Earth's 5th largest continent and is covered in ice and is a desert. Rain or snow falls infrequently and when it does snow, the snow often does not melt and builds up over many years to make large, thick sheets of ice.

Attributions

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- Figure 18.4: "Namib Desert" (CC-BY 2.0; Sonse via Wikimedia Commons)
- Figure 18.5: Derivative of “Orographic Effect” (CC-BY-SA 2.0; Meg Stewart via Flickr) by Chloe Branciforte
- Figure 18.6: “Landsat Image Mosaic of Antarctica” (Public Domain; USGS, NASA, NSF, and the British Antarctic Survey)

Weathering and Erosion Processes in Deserts

During our sedimentary section we discussed weathering and erosion in detail. Remember that water acts as a major agent of both physical and chemical weathering, and in desert climates water is scarce, which overall results in a much slower rate of weathering. When large amounts of precipitation fall over a short period of time, however, like during the rainy season, **flash floods** and **mud and/or debris flows** are likely to occur and are responsible for large amounts of rapid weathering and erosion (**Figure 18.7**).

Figure 18.7: A series of unusual storms in October 2015 caused large amounts of damage throughout Death Valley National Park. Flash floods destroyed significant portions of multiple roads and heavily damaged several historic structures at Scotty's Castle and deposited debris in Devils Hole.

As we learned about surface runoff in Chapter 9, the maximum particle size water can carry is tied to velocity, so high velocity flash floods play a major role in desert deposition. They are also a serious concern for desert travelers who must pay attention to regional weather. Surface runoff in deserts struggle to infiltrate the ground because the flow compacts the surface, plants are less common to slow flows, and soils in deserts can become hydrophobic. Water typically runs off as **sheetwash** to stream channels called **arroyos** or a dry wash that may be dry for part or most of the year. Dry ephemeral channels fill quickly, creating a mass of water and debris that charges down the channel, sometimes overflowing the banks of the arroyo. People entering or camping in such channels have been swept away by these sudden flash floods.

Wind is another notable agent of weathering and erosion in deserts. Lower energy than water, wind transport can typically move sand, silt, and clay-sized sediment, but, just like water, maximum load size is dependent on velocity. Typically, silt and clay-sized material, like in dust storms or **haboobs**, can be carried miles up into the atmosphere and can travel across the globe. Dust from the Sahara Desert can reach the US and is found in sediment cores from the Atlantic Ocean. Dust from the Gobi Desert in China can reach the western United States and can be found in sediment cores in the Pacific Ocean.

Figure 18.8: Desert sand composed almost exclusively of rounded quartz grains. ©Sepp

Transported sand grains typically remain close to the surface and are moved by a process called **saltation**. Sand grains are lifted into the moving air, carried a short distance, then drop and impact the surface, dislodging other sand grains and continuing the cycle. These wind-blown saltating sand grains are consequently well-rounded and have frosted surfaces (**Figure 18.8**). In areas where sand accumulates to form sand dunes, clumps of vegetation often anchor sediment on the desert surface. However, saltation from winds may still be sufficient to move or remove materials not anchored by vegetation causing bowl-shaped depressions in the sand called **blowouts**.

The saltating sand sandblasts and carves features into the bedrock, including distinctly shaped rocks and boulders called **yardangs** and faceted rocks called **ventifacts**. The wind is also responsible for the formation of **desert pavement**, a surface covered with closely packed, interlocking angular or rounded rock fragments of pebble and cobble size (**Figure 18.9**). Commonly many of these desert surfaces will also have **desert varnish** (desert patina or rock rust), a thin dark brown layer of clay, iron and manganese oxides that form on stable surfaces within desert environments.

Figure 18.9: Desert pavement in the Mojave Desert, east of Barstow, California in San Bernardino County.

Attributions

- Figure 18.7: “Flood Damage Worse than Originally Realized” (Public Domain; NPS)
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Desert Landforms

In deserts like the Mojave and Great Basin of California, streams drain the mountains through canyons that emerge into adjacent valleys. As the stream emerges from these narrow canyons, the sediment they carry spreads out and is deposited due to the lack of confinement, low slope angle, and slower velocities. The stream channel begins to fill with this conglomeratic material, and the stream must adjust and deflects around the fill. This process will continue to occur, causing the stream to be deflected back and forth, developing a braided system and constructing a fan shaped feature called an **alluvial fan**. Alluvial fans continue to grow and may eventually coalesce with neighboring fans to form an apron of alluvium along the mountain front called a **bajada**. Eventually mountains become buried in their own erosional debris and are referred to as **inselbergs** or “island mountains”.

Figure 18.10: Alluvial fan in Death Valley, California (top of photo), seen from source area of Black Mountains at Dante's View.

Where the desert valley is an enclosed basin, streams entering it do not drain out but the water is removed by evaporation. This forms a flat dry lake bed called a **playa**. The playa lake that fills this flat area may cover a large area and be only a few inches deep, and that only after a heavy

thunderstorm. Playa lakes and desert streams that fill and flow only after rainstorms are frequently **intermittent** or **ephemeral**.

Can You Dig It?

The famous **Racetrack Playa** of Death Valley National Park perplexed scientists for years, as they attempted to explain the independent movement of cobbles and large boulders along flat surfaces (**Figure 18.11**). In 2014, several experimental and observational studies confirmed that thin layers of ice allow the stones to slip along the ground, with high winds providing propulsive energy.

Figure 18.11: Racetrack playa and the famous sailing rocks.

Want to read more? Check out the article in PLOS ONE, an inclusive journal freely accessible to all. Norris RD, Norris JM, Lorenz RD, Ray J, Jackson B (2014) *Sliding Rocks on Racetrack Playa, Death Valley National Park: First Observation of Rocks in Motio*n. PLOS ONE 9(8): e105948. https://doi.org/10.1371/journal.pone.0105948

Attributions

- Figure 18.10: "Alluvial Fan in Death Valley" (Public Domain; Wilson44691 via Wikimedia Commons)
- Figure 18.11: Derivative of “Racetrack Playa, Death Valley National Park” (CC-BY-SA 2.0; Gregory "Slobirdr" Smith via Wikimedia Commons) and “Racetrack Playa in Death Valley National Park” (CC-BY-SA 4.0; Lgcharlot via Racetrack Playa, Death Valley National Park) by Chloe Branciforte

Sand Deposits

While deserts are defined by dryness, not sand, the popular conception of a typical desert is a sand-sea called an **erg**: a broad area of desert covered by a sheet of fine-grained sand often blown by aeolian (wind) forces into dunes. The best-known erg is the Empty Quarter (Rub' al Khali) of Saudi Arabia, but other ergs exist including in parts of Death Valley National Park.

Sand builds up the crest of the dune and pours over the top until the leeward (downwind or slip) face of the dune reaches the **angle of repose**, the maximum angle which will support the sand pile. Dunes are unstable features and move as the sand erodes from the stoss side and continues to drop down the leeward side covering previous stoss and slip-face layers and creating **cross-beds**. Fossil ergs are represented by the Navajo Sandstone and Zion National Park of Utah (**Figure 18.12**).

Figure 18.12: Cross-bedded Navajo Sandstone in the Jurassic of Utah.

Attributions

- Figure 18.12: "Cross-Bedded Sandstone" (CC-BY 2.0; James St. John via Flickr)

Dune Types

Dunes are complex features formed by a combination of wind direction and sand supply, and in some cases interacting with vegetation. There are several types of dunes representing variable wind direction, sand supply, and vegetative anchoring.

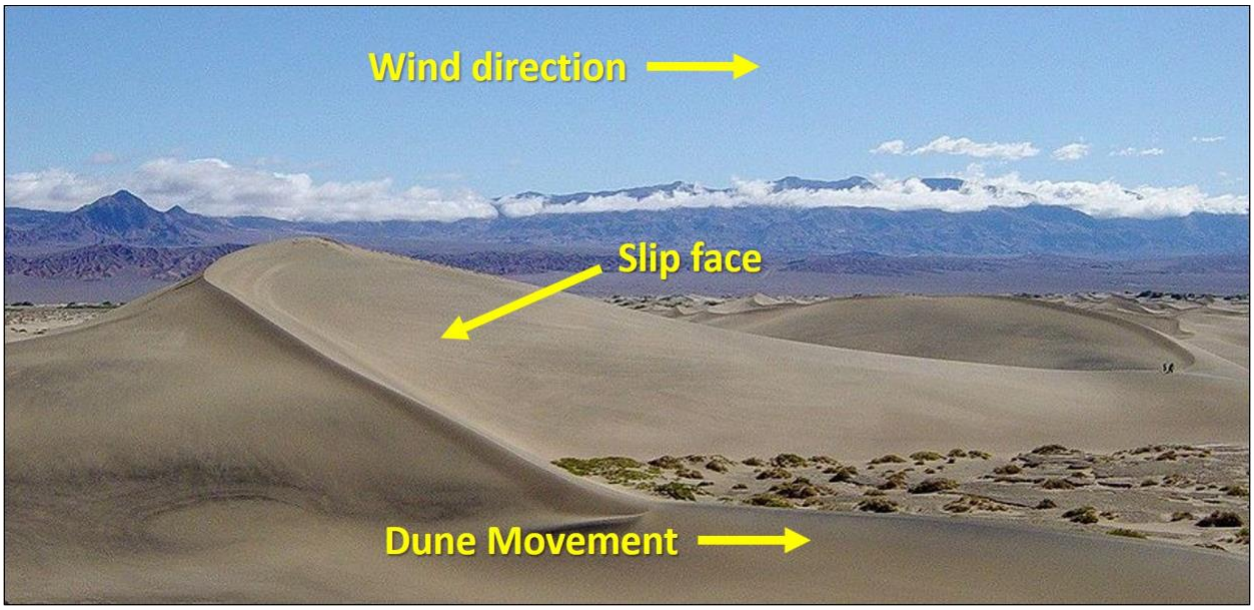


Figure 18.13: Mesquite Flat Dunes in Death Valley National Park looking toward the Cottonwood Mountains from the north west arm of Star Dune.

Crescent Dunes

- Barchan dunes form where sand supply is limited and there is a constant wind direction. Barchans migrate downwind and develop a crescent shape with wings on either side of a dune crest (**Figure 18.13**). Barchan dunes are mobile enough that they can overtake homes or even towns.
- Parabolic dunes (coastal dunes) also have a crescent shape; however, they form when vegetation anchors parts of the sand and the unanchored parts are removed and form a blowout (**Figure 18.14**).

Figure 18.14: Formation of coastal dunes in Marina Dunes Preserve west of Salinas, California.

Linear dunes

- Longitudinal dunes form when two dominant wind directions average towards the direction of elongation. This bi-directional wind flow typically produces two slip faces (**Figure 18.15**).
- **Transverse dunes** form when abundant barchan dunes merge to form linear, slightly sinuous, dunes. They lie transverse, or across, the wind direction, with the wind blowing perpendicular to the ridge crest (**Figure 18.15**).

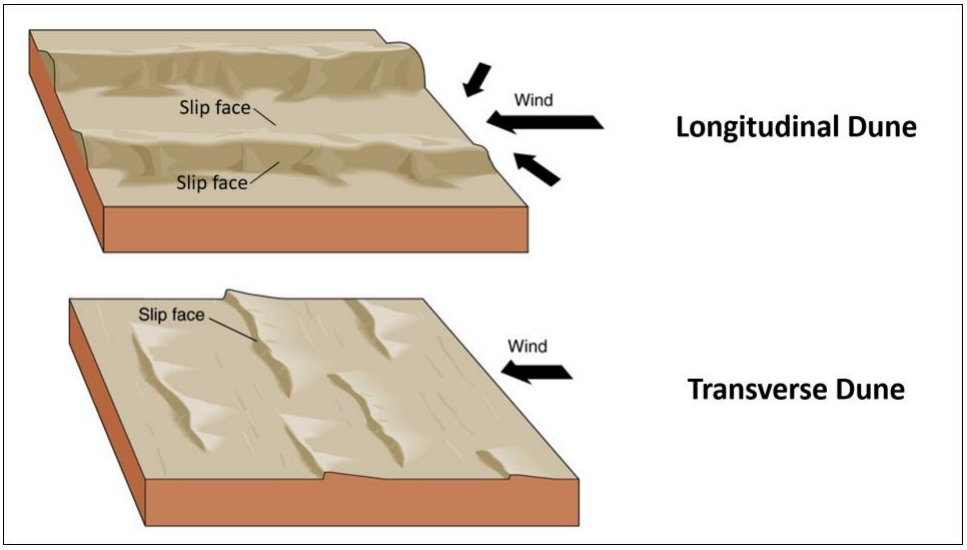


Figure 18.15: Formation of linear dunes.

The Eureka Dunes (**Figure 18.16**), are the tallest dunes in California, and the second tallest in North America. They are likely a combination of both longitudinal and transverse dunes, with winds averaging east-west.

Figure 18.16: Eureka Dunes within Death Valley National Park, CA

Star dunes form where the wind direction is variable, forming the distinct star shape. Sand supply can range from limited to quite abundant. Mobility is low, as they tend to not move in a dominant direction (**Figure 18.17**).

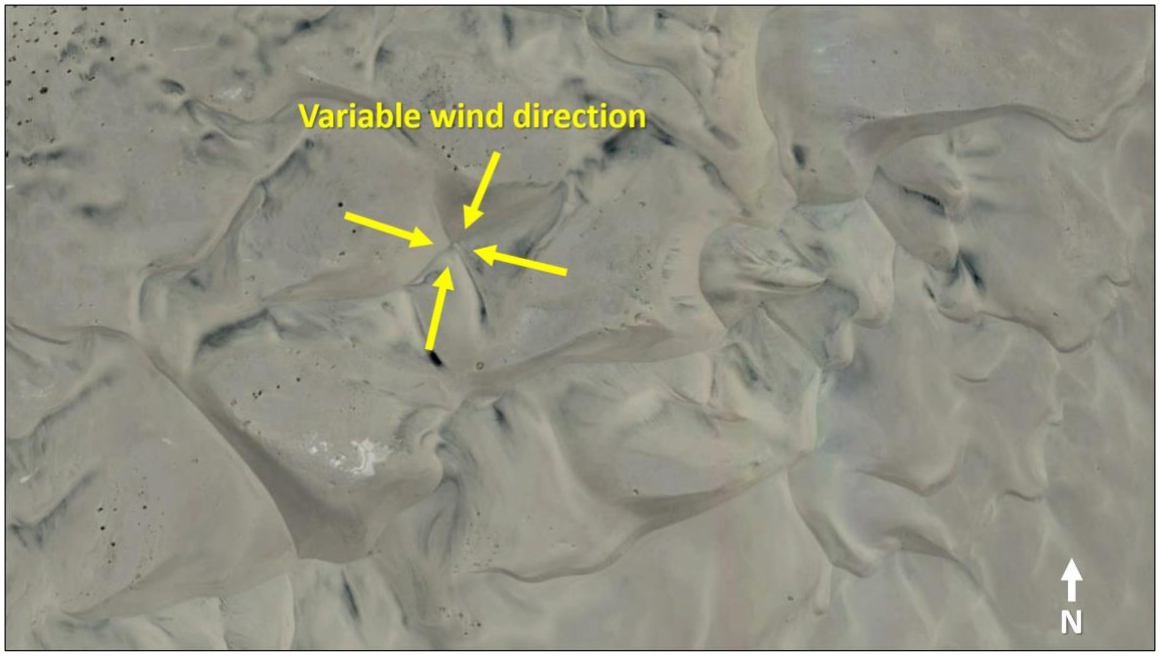


Figure 18.17: Panamint Dunes, which are star dunes, within Death Valley National Park, California.

Attributions

- Figure 18.13: Derivative of “Mesquite Sand Dunes” (CC-BY-SA 3.0; Daniel Mayer via Wikipedia) by Chloe Branciforte
- Figure 18.14: “Parabolic Dunes” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)
- Figure 18.15: Derivative of “Longitudinal and Transverse Dunes” (CC-BY 3.0; Po ke jung via Wikimedia Commons and Wikimedia Commons) by Chloe Branciforte
- Figure 18.16: “Eureka Dunes” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)
- Figure 18.17: “Panamint Star Dunes” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)

Desertification

Climate change and other human activities, such as unsustainable farming practices, livestock overgrazing, and overuse of available water can degrade previously **arable** land, a process known as **desertification**. This is a serious problem worldwide and will continue to worsen with climate change. **Figure 18.18** shows areas of the world and their vulnerability to desertification. Note the red and orange areas in the western United States. Mitigating the desertification process includes both societal steps and individual education on alternatives to harmful activities.

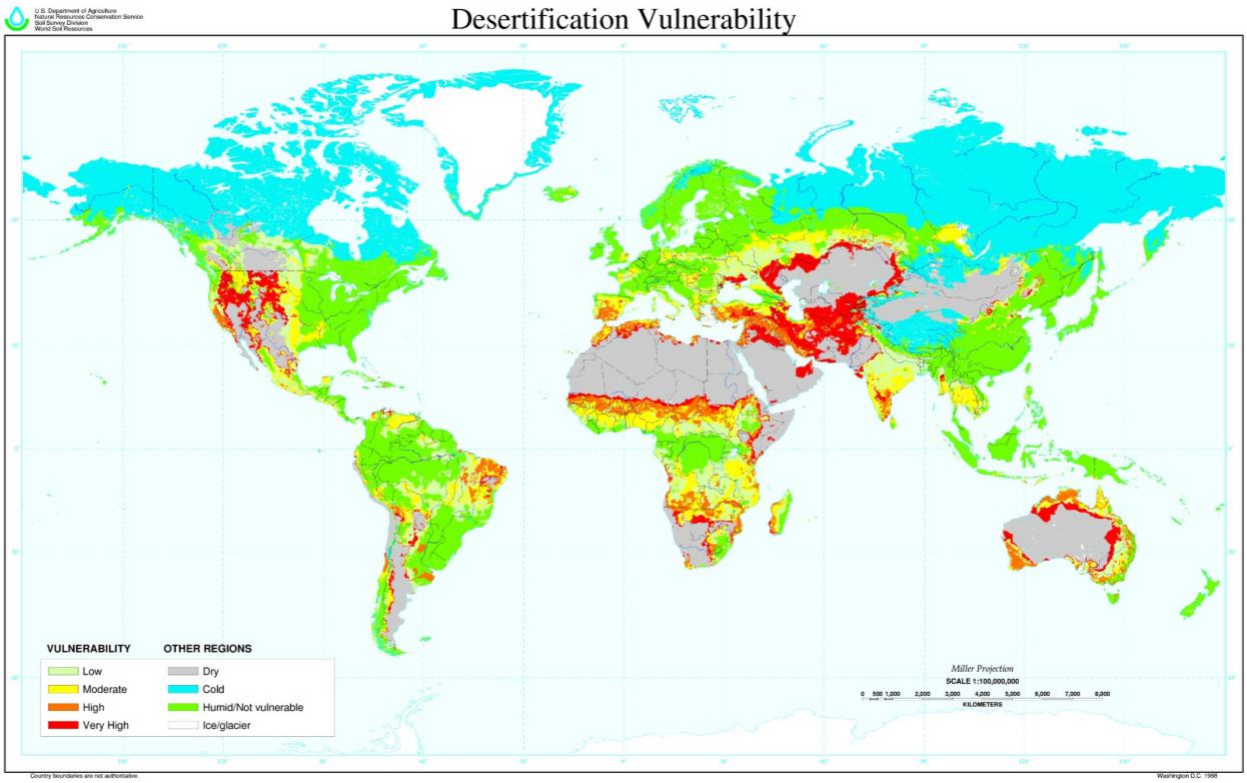


Figure 18.18: Global Desertification Vulnerability Map.

Attributions

- Figure 18.8: “Global Desertification Vulnerability Map” (Public Domain; USDA-NRCS, Soil Survey Division)

Activity 18A: Identifying Desert Landforms

1. **Figure 18.19** is a section from the topographic map and an aerial image from Death Valley National Park.

    a. Identify the desert landform at A.

    b. Examine the area around the yellow star. Identify the river flow pattern here.

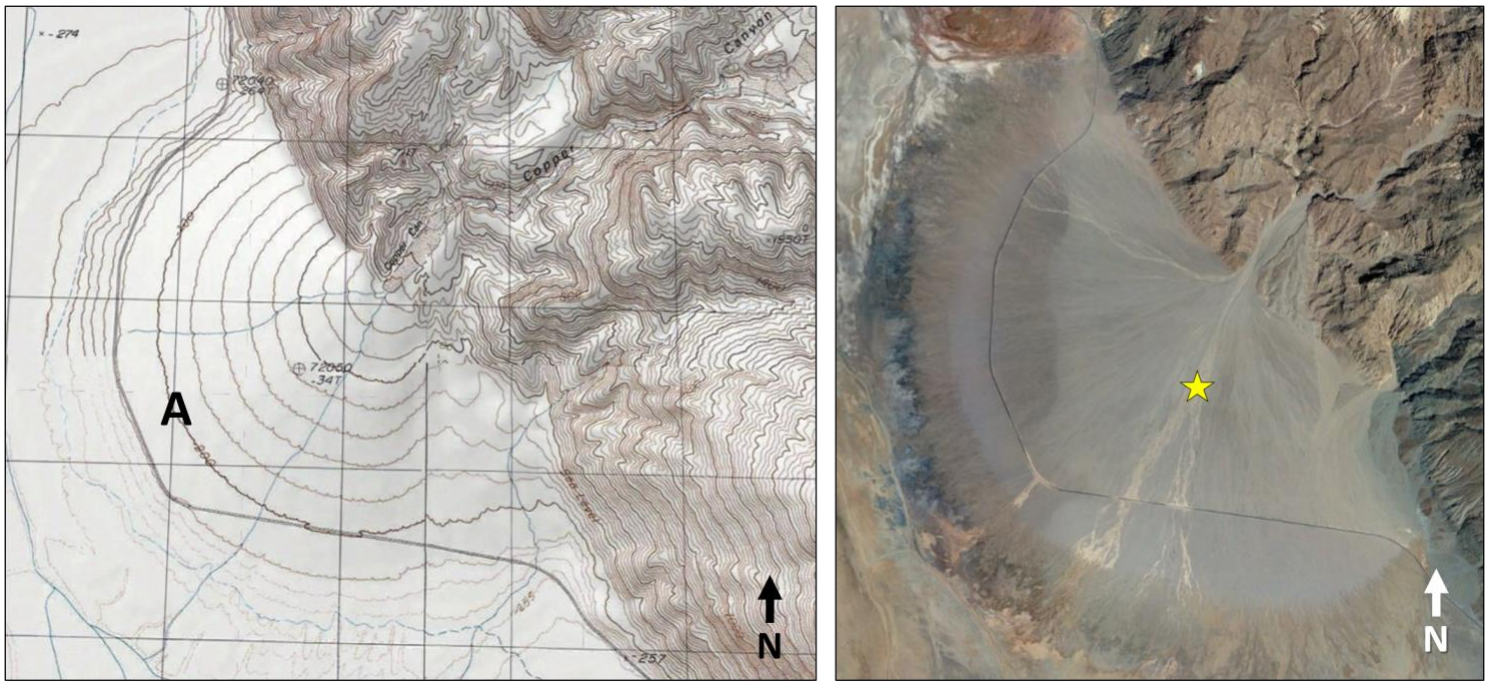


Figure 18.19: Landforms for Question 1, Activity 18A.

2. **Figure 18.20** shows Badwater Basin in Death Valley National Park.

   a. Identify the desert landform outlined in yellow at B.

   b. In general, how would the sediment size change moving from the mountains out into the valley?

Figure 18.20: Landform for Question 2, Activity 18A.

3. **Figure 18.21** is of Panamint Valley located at the northern end of Death Valley National Park.

    a. Which desert landform is currently located at C?

    b. Which desert landform would be present WITHOUT the water?

    c. What minerals would likely develop here?

Figure 18.21: Landform for Question 3, Activity 18A.

Attributions

- Figure 18.19: “Desert Landforms and Drainage” (CC-BY 4.0; Chloe Branciforte via Earth Point and Google Earth, own work)
- Figure 18.20: “Badwater Basin” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)
- Figure 18.21: “Death Valley exit SR 190 view Panamint Butte Flash Flood” (CC-BY-SA 3.0; Tuxyso via Wikimedia Commons)

Activity 18B: Identifying Sand Dunes

1. **Figure 18.22** is of a dune field at the northern end of Death Valley National Park.

    a. Which type of sand dune is located around location D?

    b. Which direction is the wind likely blowing? *Hint: use the north arrow to help* or *draw directly on the image*.

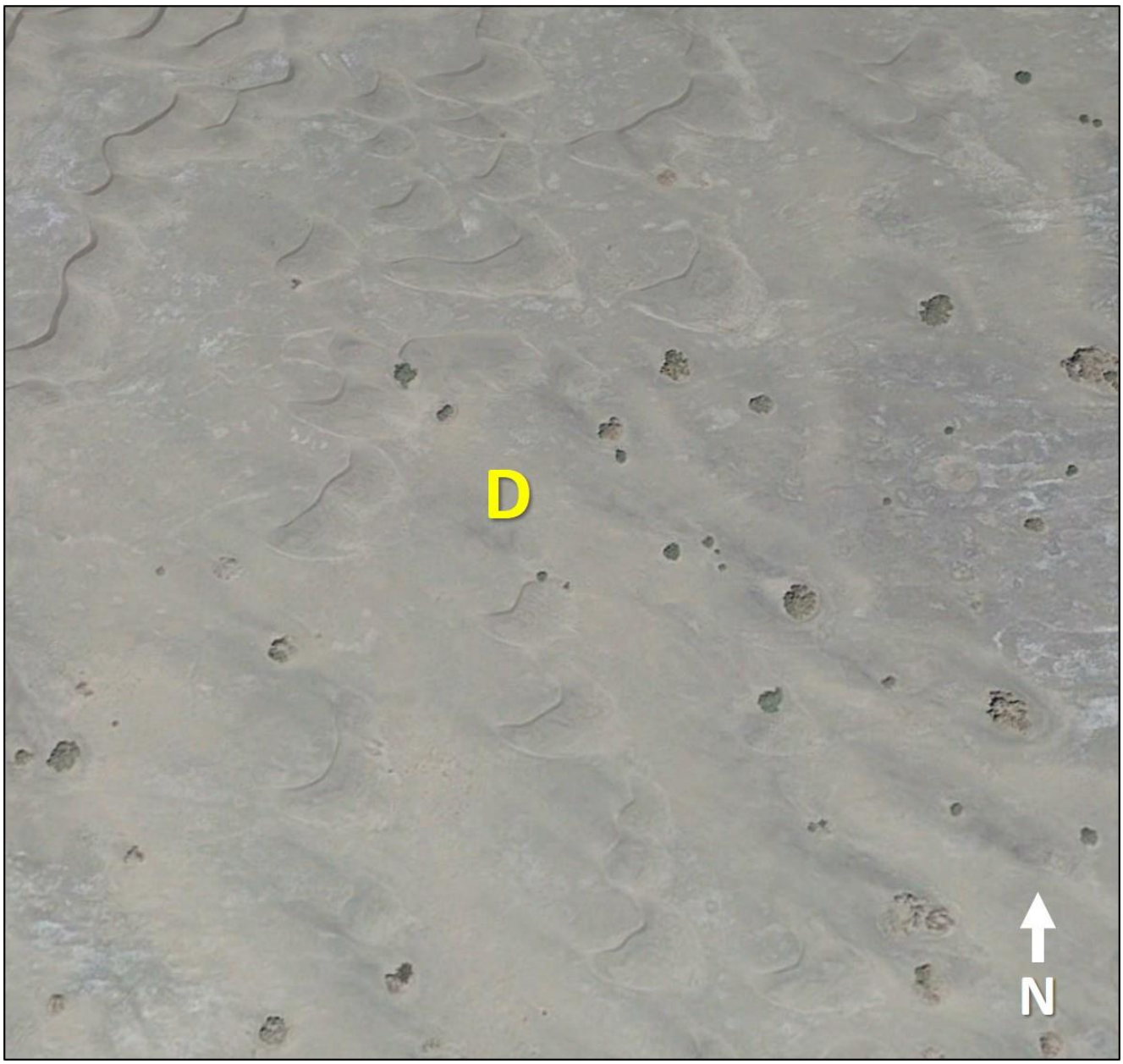


Figure 18.22: Landform for Question 1 of Activity 18B.

2. **Figure 18.23** is of a dune field at the northern end of Death Valley National Park.

    a. Which category of sand dune is located around location E?

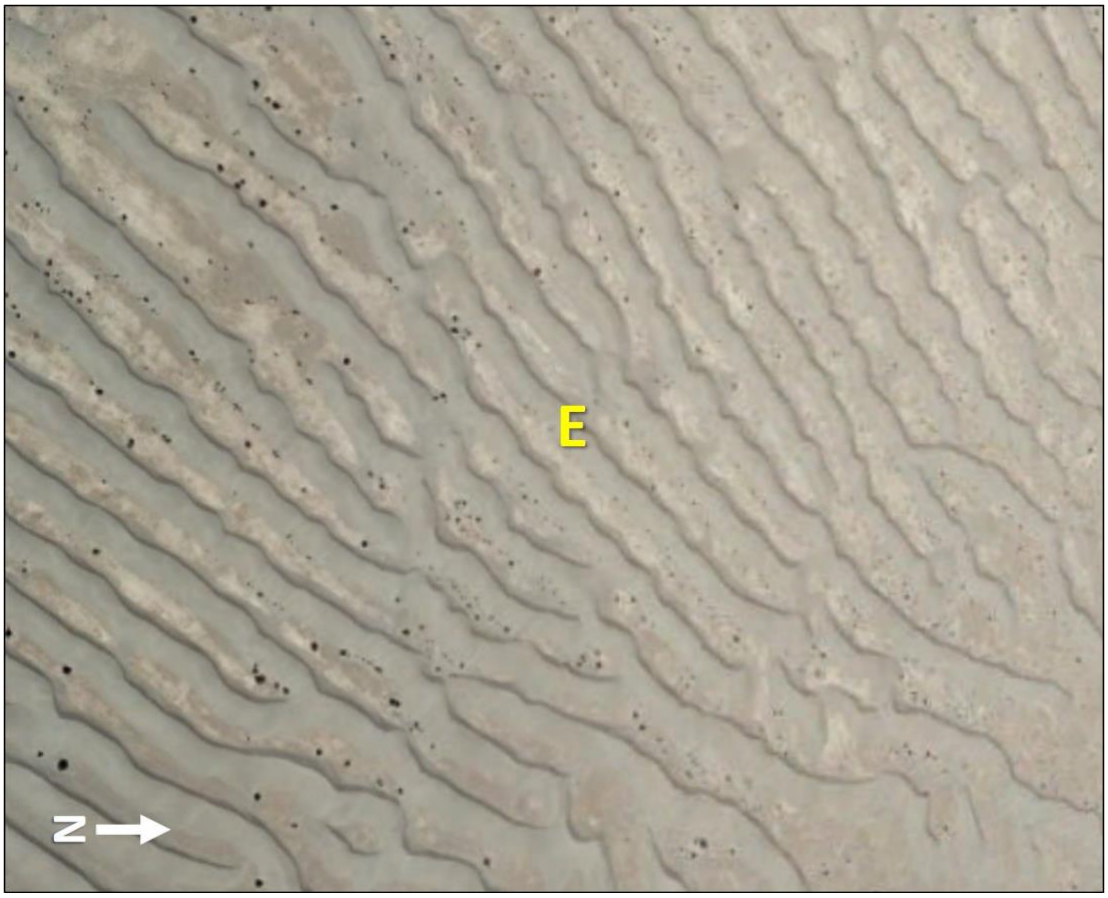


Figure 18.23: Landform for Question 2 of Activity 18B.

3. Open the browser version of Google Earth and enter the location, 36°39'45.1"N 117°06'14.1"W into the search bar. Zoom in and out to examine this region in detail. There are a number of dune fields within this region of Death Valley. What is the likely dominant wind direction in this part of Death Valley?

    a. How can you tell?

4. **Figure 18.24** is from the Eureka Dune Field, located at the northern edge of Death Valley National Park.

    a. Which type of sand dune is located at F?

    b. Which does this type of sand dune indicate about the wind direction?

Figure 18.24: Landform for Question 4 of Activity 18B.

Attributions

- Figure 18.22: “Dune Field in Death Valley National Park” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)
- Figure 18.23: “Dune Field at the Northern End of Death Valley National Park” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)
- Figure 18.24: “Eureka Dune Field” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)

Activity 18C: Identifying Desert Categories

1. California is home to two of the three major desert categories discussed in this manual. Using the map of California (**Figure 18.25**) below,

    a. Identify the desert category where G is located:

    b. Identify the desert category where H is located:

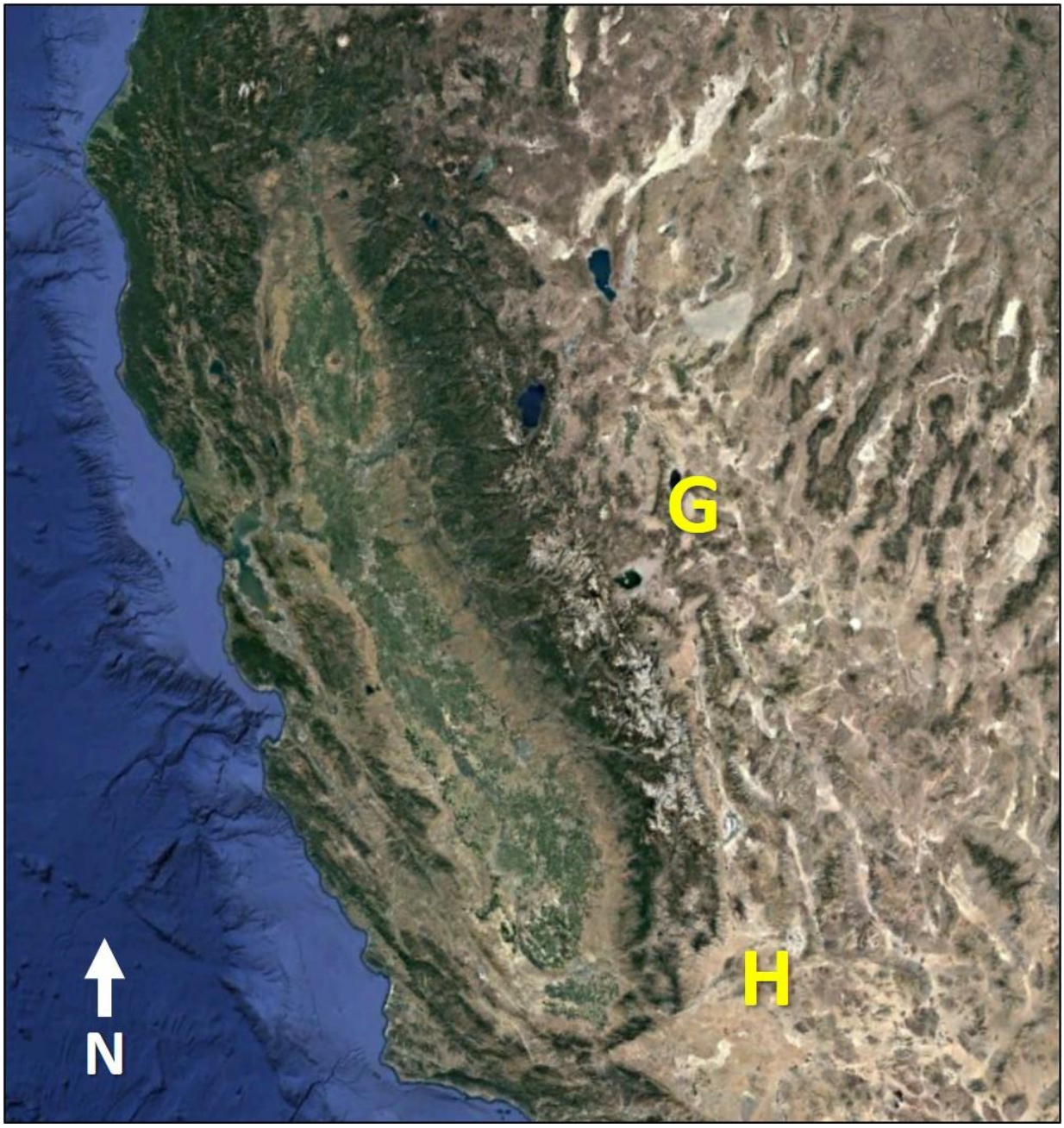


Figure 18.25: Landforms for Question 1, Activity 18C.

2. California does not have a polar desert. In the reading above Antarctica is discussed as a major polar desert. Complete a simple Google search and identify a different polar desert somewhere else in the world.

    a. Polar desert name:

    b. Approximate latitude and longitude:

3. Complete a simple Google search and identify a desert not discussed in this lab and not present in California.

    a. Desert name:

    b. Country/State/Province location:

    c. Approximate latitude and longitude:

    d. Identify something unique or unusual about your desert selection:

Attributions

- Figure 18.25: “Eureka Dune Field” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)

Chapter 19: Glacial Processes and Landforms

Learning Outcomes

After completing this chapter, you should be able to:

- ✔ Distinguish between glacial types.
- ✔ Describe and identify the various glacial landforms.
- ✔ Describe and identify the various glacial deposits.

Thumbnail for Chapter 19:

Thumbnail: "Palisade Glacier and Mount Sill" (CC-BY-SA 2.0; Dave Ciskowski via Flickr)

What Is a Glacier?

A **glacier** is a long-lasting accumulation of ice and snow that is large enough to flow down slope under the influence of its own weight. Typically, glaciers are classified by their size and location. Glaciers will develop in areas where 1) the average annual temperatures are close to freezing (32°F or 0°C), 2) the winter season produces significant accumulations of snow, and 3) the temperatures throughout the year remain low enough to retain any of the winter snow accumulation through to the following winter season. Should these criteria be met over multiple decades, the continued accumulation of snow will generate a large enough mass to induce a change from snow to glacial ice. Overall, glaciers are an important component of the **cryosphere** and are sensitive indicators of changing climate (see Chapter 20 for additional information).

Figure 19.1: Palisade Glacier and Mount Sill. The southernmost glacier in North America, and the largest glacier in the Sierra Nevada.

A person who studies glaciers is typically referred to as a glaciologist. Glaciology is the study of snow and ice and their physical properties. Glaciologists analyze the formation, movement, and effects of the different kinds of glaciers, for example alpine and arctic glaciers, ice caps, ice sheets, and ice shelves. A large part of the research conducted by glaciologists analyzes how

glaciers and ice caps move and change in response to climate change and how these changes in turn influence climate and the surrounding environment. Therefore, many glaciologists are also considered climate scientists. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways include environmental policy and legislation and consulting, via the private sector or state and federal agencies. Many of these career options require a college degree and postgraduate work. If this pathway is of interest to you, talk to your geology instructor for advice. We recommend completing as many math and science courses as possible. Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Attributions

- Figure 19.1: “Palisade Glacier and Mount Sill” (CC-BY-SA 2.0; Dave Ciskowski via Flickr)

What Are the Glacial Types?

Mountain, alpine, or valley glaciers (**Figure 19.2**) typically develop in mountainous regions, often flowing out of **icefields** that span several peaks or even an entire mountain range. The largest mountain glaciers are found in Arctic Canada, Alaska, the Andes in South America, and the Himalaya in Asia.

Figure 19.2: The Fraser Glacier in Glacier Bay National Park, Alaska is a valley glacier, confined by mountains on either side.

Piedmont glaciers form where steep valley glaciers spill onto relatively flat plains and spread out into bulb-like lobes.

Ice sheets are enormous continental masses of glacial ice and snow expanding over 50,000 square kilometers (19,305 square miles). Currently, the only ice sheets are found in **Antarctica** and **Greenland** (**Figure 19.3**). **Ice caps** are miniature ice sheets, covering less than 50,000 square kilometers (19,305 square miles) and forming primarily in polar and subpolar regions.

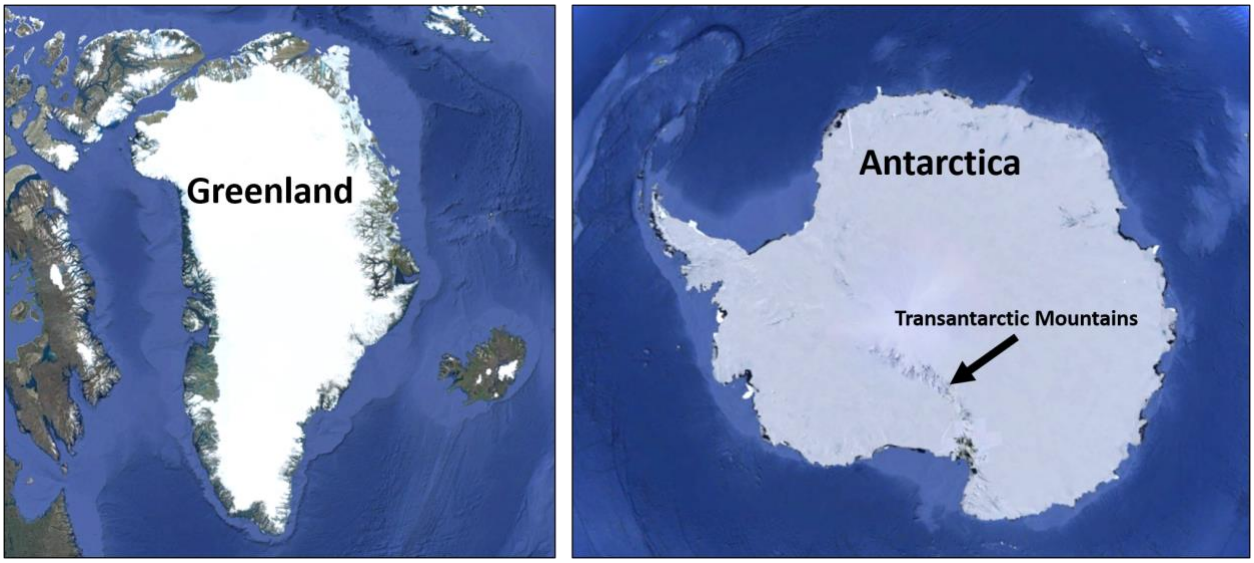


Figure 19.3: Earth's current ice sheets, Greenland and Antarctica.

Ice shelves occur when ice sheets extend over the sea and float on the water. They range from a few hundred meters to over 1 kilometer (0.62 mile) in thickness. Ice shelves surround most of the Antarctic continent. **Sea ice** is NOT a glacier, as glaciers develop only on land; however, much of the world's sea ice is enclosed within the polar regions.

Attributions

- Figure 19.2: “Types of Glaciers: Valley Glacier, Fraser Glacier” (Public Domain; Jacob W. Frank/NPS Photo via Flickr)
- Figure 19.3: “Ice Sheets” (CC-BY 4.0; Chloe Branciforte via Google Earth, own work)

How Does a Glacier Develop?

Glaciers require very specific climatic conditions to develop. Most form in polar latitudes or high-altitude regions, where accumulation of winter snow and ice is greater than its loss in the summer. As snow accumulates during winter, compression forces the older snow to recrystallize. After about a year, a denser, more compressed layer called **firn** develops (**Figure 19.4**). With enough pressure (from sequential burial) and time, firn will transform into crystalline glacial ice. True glacier ice takes hundreds of years to develop.

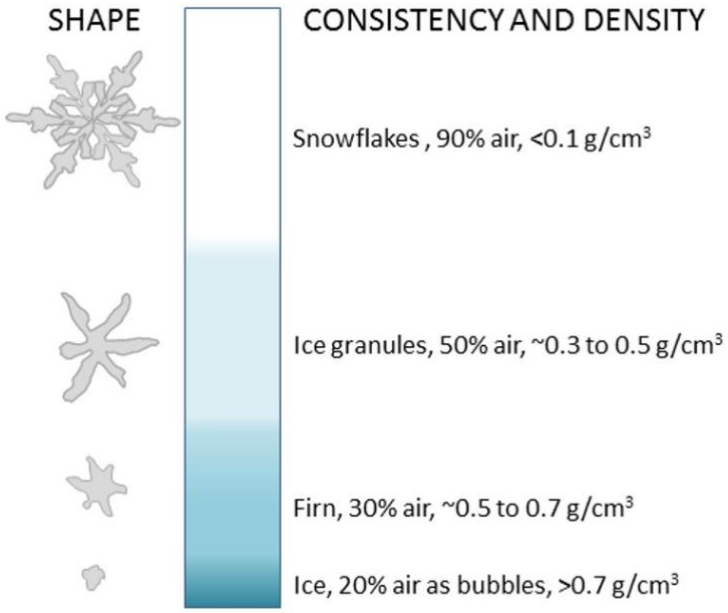


Figure 19.4: The formation of glacial ice.

As the interconnecting air passages between the firn grains are sealed off, **air bubbles** will be formed. These air bubbles are important for exploring climate and the events of the geologic, or historic, past.

Can You Dig It?

Why is Glacial Ice Blue? Ice only appears blue when it is sufficiently consolidated such that air bubbles cannot interfere with the passage of light. Without the scattering effect of air bubbles, light can penetrate ice undisturbed. In ice, the absorption of light at the red end (long wavelengths) of the spectrum is greater than at the blue end (short wavelengths). In general, the deeper light energy travels within a glacier, the more longwave colors are lost. About two meters into the glacier, most of the red colors are gone. The short wavelengths are left behind, which results in the distinct blue color we see (**Figure 19.5**).

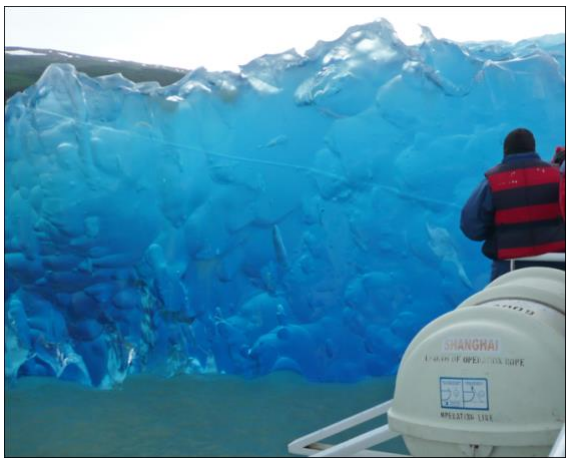


Figure 19.5: Blue glacial ice.

Attributions

- Figure 19.4: “Glacial Ice Development” (CC-BY 4.0; Steven Earle via OpenText)
- Figure 19.5: “Blue Glacial Ice” (CC-BY 2.0; James St. John via Flickr)

How Do Glaciers Move?

Glaciers flow outwards and downwards under the pressure of their own weight and the forces of gravity. Valley glaciers tend to flow down valleys, with the fastest flow rate in the upper central region of the glacier. Friction along the valley glaciers' sides and base cause the flow rate to be much slower, whereas continental ice sheets flow outward in all directions (**Figure 19.6**).

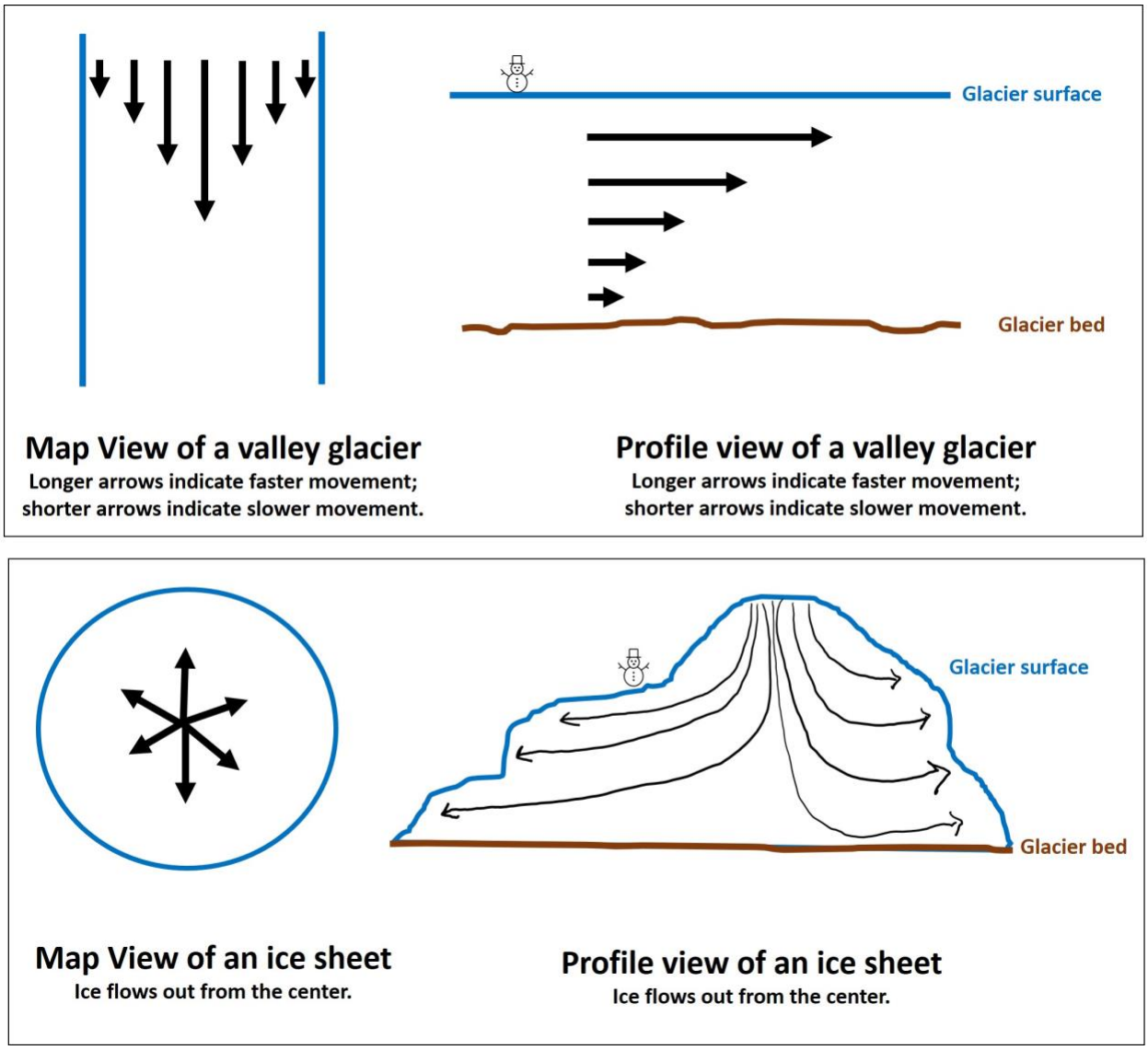


Figure 19.6: *Top left:* map view of a valley glacier. Faster movement along center, and slower movement along sides. *Top right:* profile view of a valley glacier. Faster movements towards the top, slower movement towards the glacial bed. *Bottom left:* map view of an ice sheet. Ice flows out in all directions. *Bottom right:* profile view of an ice sheet. ice flows out from the center.

Glacial movement happens mostly through internal deformation of the ice, and by sliding over the rocks and sediments at the glacier's bed or base. Internal deformation occurs when the weight and mass of a glacier cause it to spread out due to gravity. Sliding primarily occurs due to the presence of meltwater at the bed; more meltwater reduces friction at the base and increases the likelihood of movement. In some glaciers, an excess of meltwater can induce glacial surge events, where a glacier will advance quickly during a short period of time (up to 100x the normal movement). During rapid uneven movement, some glaciers will develop cracks or **crevasses**.

Attributions

- Figure 19.6: “Glacial Movement” (CC-BY 4.0; Chloe Branciforte, own work)

What Is Glacial Advance and Retreat?

Glacial advance and retreat are dictated by the amount of material entering the **zone of accumulation** and exiting the **zone of ablation**. The glacier will advance (i.e. extend its **terminus** down the length of the valley) when accumulation exceeds ablation. For this to occur, more snow and ice must fall and accumulate than is melted or evaporated away. The glacier will recede (i.e. the terminus retreats up the length of the valley) when ablation exceeds accumulation. More snow and ice is melted or evaporated from the zone of ablation than is added to the accumulation zone. (**Figure 19.7**). ***It is important to remember that even in retreat, glaciers are always moving forward***. You can liken their movement to the conveyor belts we put our groceries on at the store.

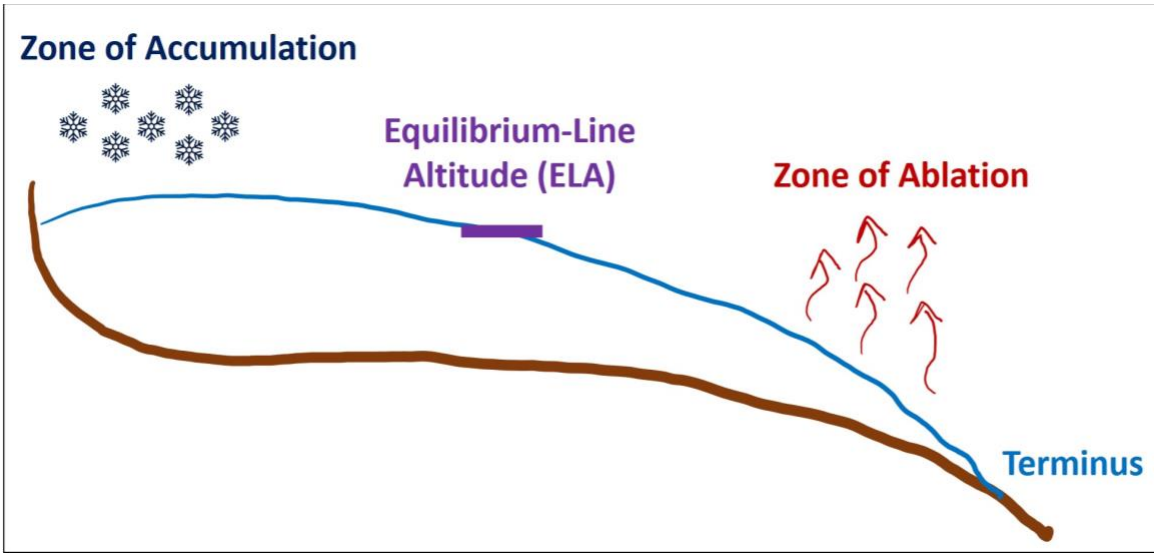


Figure 19.7: The zones of accumulation and ablation.

Over the last century, we have witnessed many glaciers retreating worldwide. This has become an important marker for global climate change. Here in the US, many of our National Parks contain glaciers which are heavily monitored, including at Yosemite National Park here in California, but also Glacier National Park in Montana and the many National Parks and glaciated areas in Alaska.

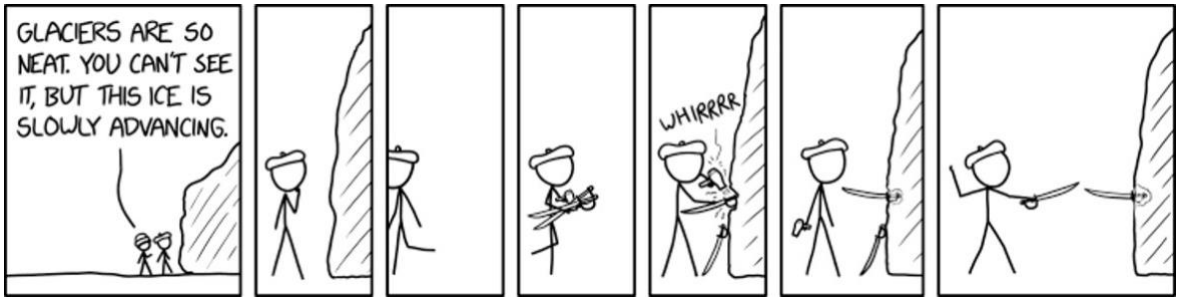


Figure 19.8

Attributions

- Figure 19.7: “Zone of Accumulation and Ablation” (CC-BY 4.0; Chloe Branciforte, own work)
- Figure 19.8: “Glacier” (CC-BY-NC 2.5; xkcd via xkcd.com)

What Are Milankovitch Cycles?

Over a century ago, Serbian scientist Milutin Milankovitch hypothesized the long-term, collective effects of changes in Earth's position relative to the Sun were a strong driver of Earth's long-term climate and responsible for triggering the beginning and end of **glacial periods** (Ice Ages). Milankovitch determined that over time, Earth's movement in space affects the amount of radiation received from the sun. Collectively, his ideas are known as the **Milankovitch Cycles** and include the following patterns of motion.

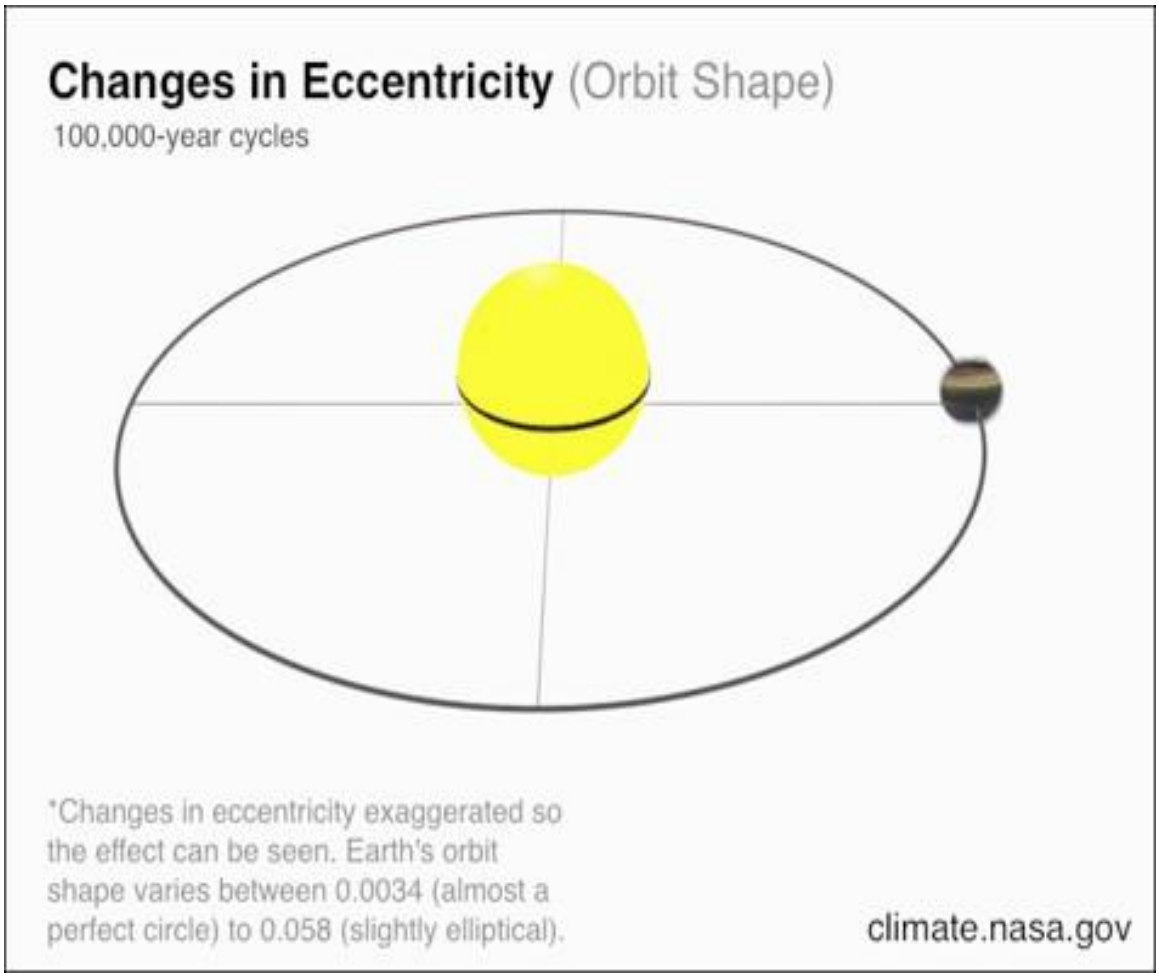


Figure 19.9: Eccentricity: orbit shape.

Eccentricity, the overall shape of Earth's orbit around the Sun, alternates between more circular and more elliptical in a cycle that spans about 100,000 years, in part due to the gravitational influence of the gas giants, Jupiter and Saturn. Currently, Earth's eccentricity is near its least elliptic (i.e. most circular) and is very slowly decreasing (**Figure 19.9**). For GIFS visit this NASA page.

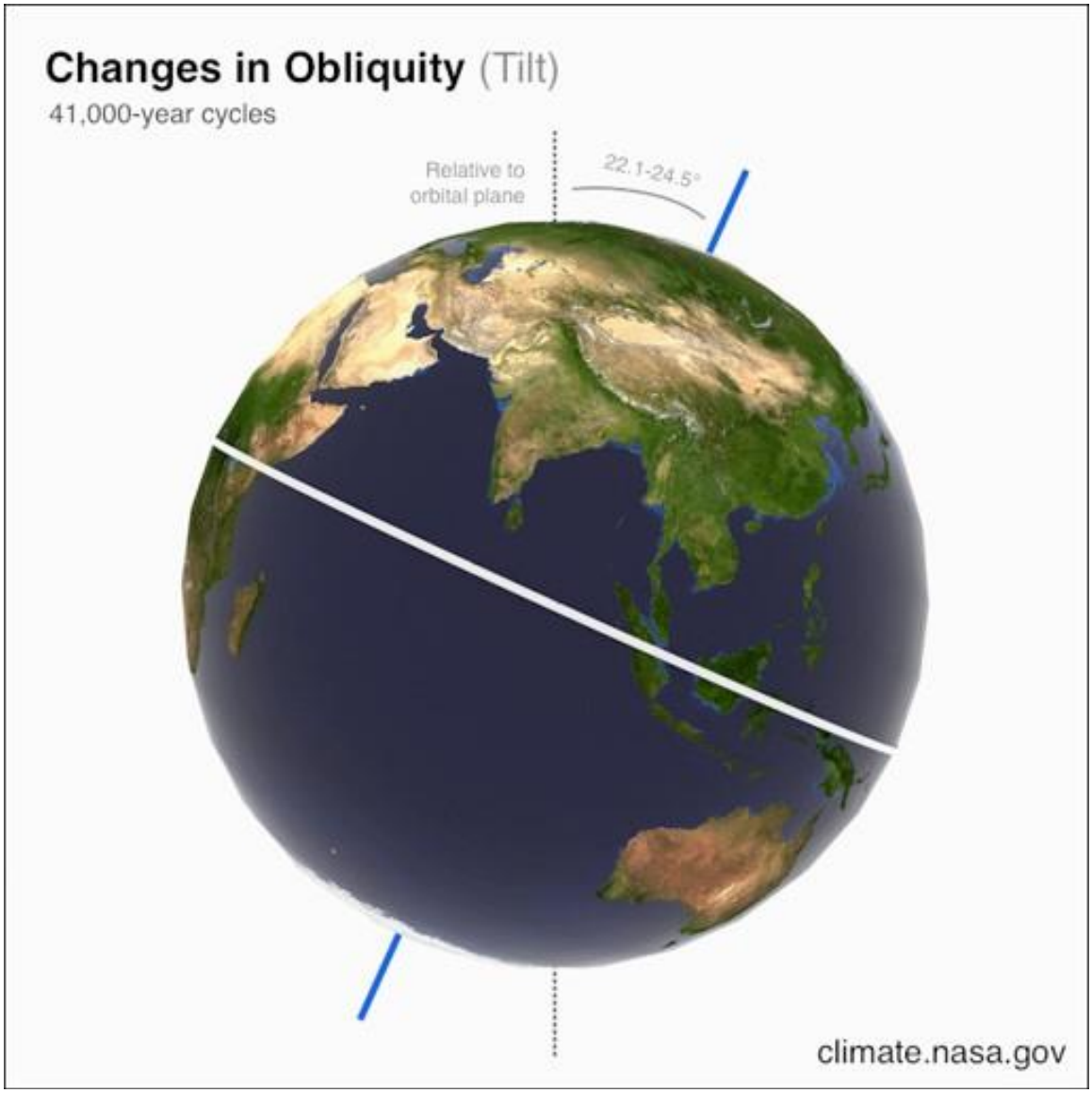


Figure 19.10: Obliquity: axial tilt.

Obliquity is the angle of Earth's axis of rotation relative to its ecliptic plane around the Sun. Obliquity is the reason Earth has seasons and is a very strong control on Earth's climate and glacial periods. Typically, Earth's obliquity varies between 22.1 and 24.5 degrees in a cycle that spans about 41,000 years, with minimum tilt favoring glaciation and maximum tilt promoting interglacial periods. Earth's axis is currently tilted 23.4 degrees and is very slowly decreasing towards minimum tilt (**Figure 19.10**). For GIFS visit this NASA page.

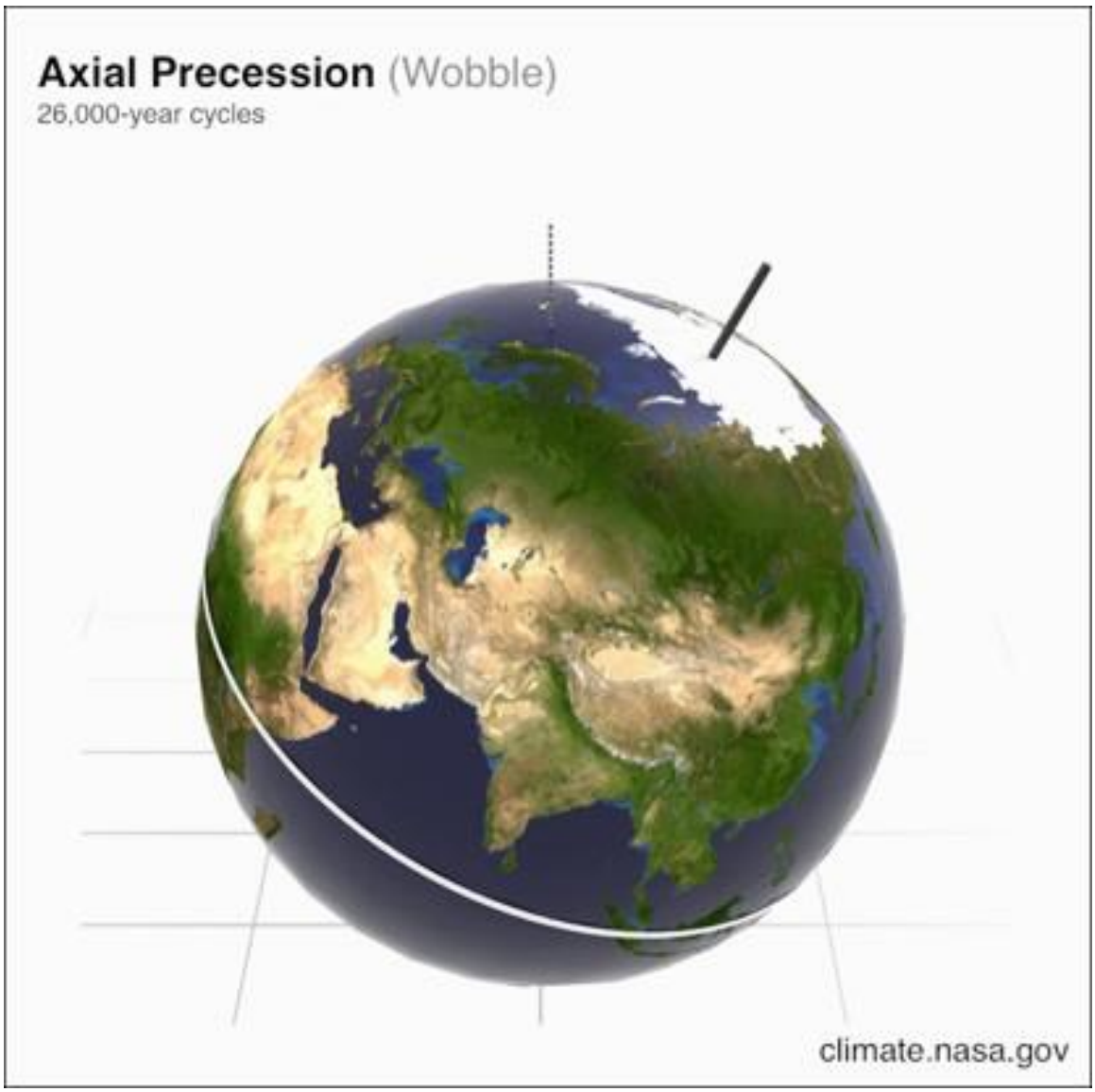


Figure 19.11: Axial precession: wobble.

Precession is the slight wobble of Earth as it rotates on its axis. This wobble is due to tidal forces caused by the gravitational influences of the Sun and Moon. The direction of wobble is determined relative to the fixed positions of stars; Earth is currently fixed to Polaris in the northern hemisphere but may wobble toward other North Stars, including Thuban and Kochab. The cycle of axial precession spans about 25,000 years (**Figure 19.11**). For GIFS visit this NASA page.

When the cycles occur together at the same interval, they can influence Earth's climate, and with other factors in place may encourage a **glacial period or glaciation** to occur.

Attributions

- Figure 19.9: “Milankovitch (Orbital) Cycles and Their Role in Climate” (Public Domain; NASA)
- Figure 19.10: “Milankovitch (Orbital) Cycles and Their Role in Climate” (Public Domain; NASA)
- Figure 19.11: “Milankovitch (Orbital) Cycles and Their Role in Climate” (Public Domain; NASA)

What Is a Glacial Period?

A **glaciation** is the modification of the land surface by the action of glaciers. Typically, the dominant glacier will be an ice sheet, but valley glaciers will also advance during this time. At the peak of the Last Glacial Maximum (~21,000 years ago), the **Laurentide Ice Sheet** covered most of northern North America and extended as far south as Nebraska and Illinois. During this time, major cities like Chicago, New York City, and Boston were buried beneath one to two miles of ice (**Figure 19.12**). The ice sheet essentially bulldozed the North American continent and left behind a distinct landscape and landforms. During this time, the valley glaciers in the Sierras and Rockies also grew and heavily altered their landscape.

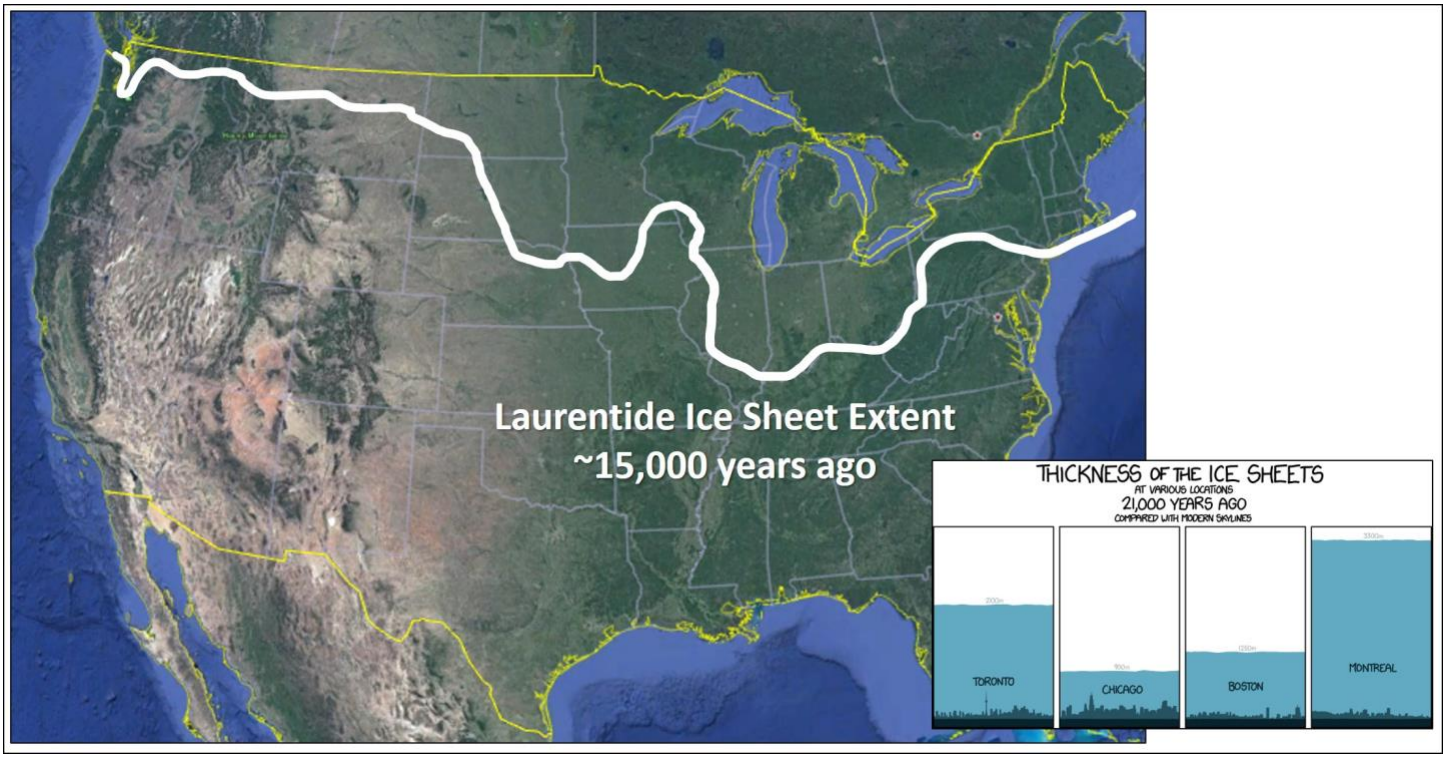


Figure 19.12: The extent of the Laurentide Ice Sheet, approximately 15,000 years ago.

Attributions

- Figure 19.12: Derivative of “Glacier” (CC-BY-NC 2.5; xkcd via xkcd.com) by Chloe Branciforte

How Are Glacial Sediments Unique?

As glaciers flow, they plow up or push aside rock and debris, which is then left behind when the glacier recedes. As large glaciers retreat, the underlying ground surface is typically abraded of most materials, leaving scars and debris on the underlying bedrock surface. Glacial ice is responsible for a large amount of erosion, and a lot of sediment can be carried on top of (supraglacial), within (englacial), and beneath (subglacial) ice. When sediment is left behind by a melting glacier, it is called **glacial till** (**Figure 19.13**).

Figure 19.13: Pleistocene glacial tills from the Sierra Nevada Mountains of eastern California in Yosemite National Park.

Till is generally poorly sorted, angular to subrounded, with grain sizes ranging from clay and silt to pebbles and boulders. The lithified rock is referred to as **tillite** or, more generally, a **diamictite**; both signify a rock that includes a wide range of clast sizes (**Figure 19.14**).

Figure 19.14: Glacially-smoothed and striated tillite from the Precambrian of Ontario, Canada.

When glaciers retreat, they may leave behind large boulders of rock types that do not match the local bedrock, called **glacial erratics** (**Figure 19.15**). Really small clay-sized sediment frequently forms **glacial or rock flour**, which can cause glacial lakes and water bodies to have a milky appearance.

Figure 19.15: Pleistocene glacial erratic in Lassen Volcanic National Park in northern California.

Often, the sediment carried within the ice affects the underlying bedrock, or even other sediment carried by the glacier. **Glacial striations, scratches, or grooves** can be carved into the bedrock, or on the cobbles and boulders carried by the ice (**Figure 19.16**).

Figure 19.16: Pleistocene-aged glacial striations developed on lava in Lassen Volcanic National Park in northern California.

Additionally, **glacial polish**, produced by fine-sediment carried by the glacier, creates an almost mirror-like finish to the bedrock (**Figure 19.17**).

Figure 19.17: Glacial polish on the granite bedrock in the Emigrant Wilderness, Sierra Nevada, California.

Attributions

- Figure 19.13: “Alpine Glacial Till” (CC-BY 2.0; James St. John via Flickr)
- Figure 19.14: “Glacially Smoothed & Striated Tillite” (CC-BY 2.0; James St. John via Flickr)
- Figure 19.15: “Pleistocene Glacial Erratic” (CC-BY 2.0; James St. John via Flickr)
- Figure 19.16: “Glacial Striations on Lava” (CC-BY 2.0; James St. John via Flickr)
- Figure 19.17: “Glacial Polish Emigrant” (CC-BY-SA 4.0; Smack via Wikipedia)

Glacial Depositional Landforms

A **moraine** is an accumulation of glacial till derived by the grinding and erosive effects of a glacier. In valley glaciers, moraines can be produced by material falling on the sides of the glacier via landslides from the valley walls. Overall, glaciers act like conveyor belts, always flowing downslope, carrying sediments inside and on the ice and depositing them at the end of their flow and along their sides. There are few varieties of moraine that are categorized by deposition location and glacial type.

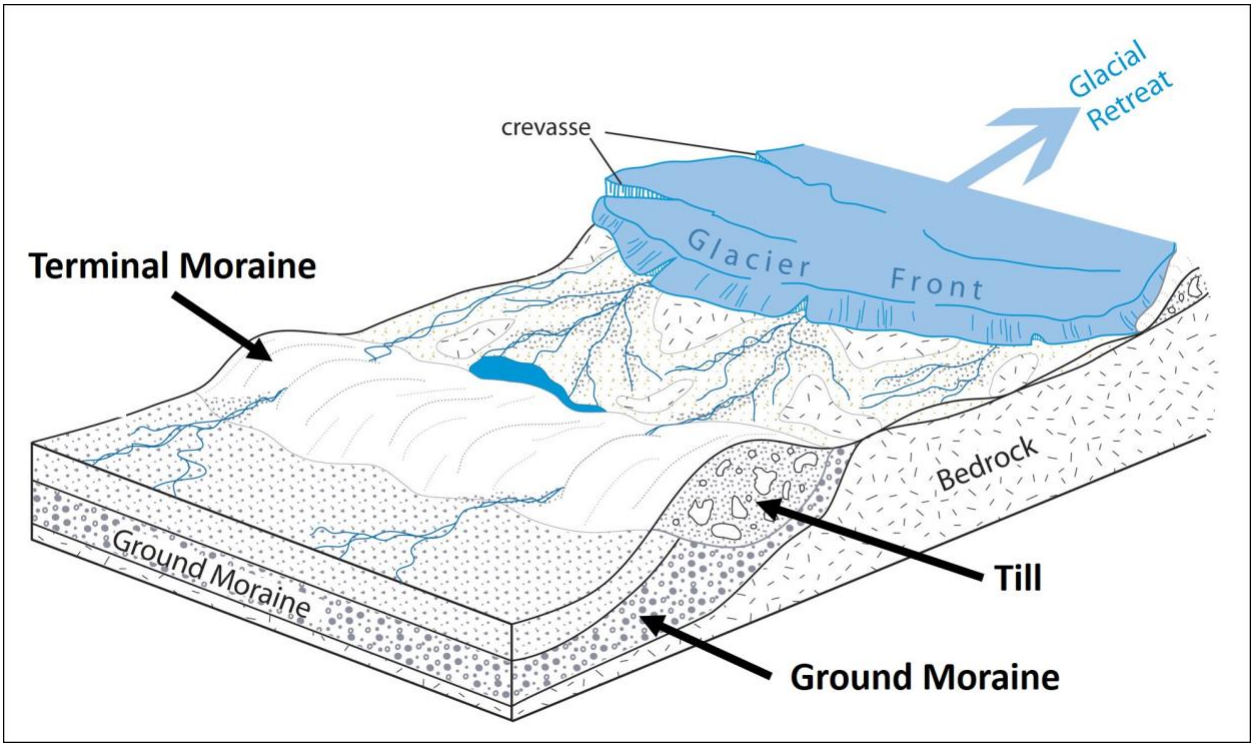


Figure 19.18: An illustration of a retreating glacier with a recent terminal moraine and a broad space between the moraine and the glacial front.

A **terminal moraine** is a ridge of unsorted till at the terminus, or farthest extent, of a glacier (**Figure 19.18**). As glaciers retreat, they typically leave behind deposits called **recessional moraines**, which are similar to terminal moraines but instead form when glacier retreat pauses. Behind the terminal and recessional moraines is a thin sheet of till on top of bedrock called the **ground moraine**. (**Figure 19.18**).

In valley glaciers, moraines located along the side of a glacier are called **lateral moraines** and mostly represent material that fell via landslides onto the sides of the glacier from the valley walls. When two tributary glaciers join, the two lateral moraines merge and combine to form a **medial moraine**. (**Figure 19.19**).

Figure 19.19: The Baldwin and Fraser Glaciers converge after flowing around an isolated peak of rock in Wrangell-St. Elias National Park, Alaska.

Other depositional landforms can be produced by meltwater streams as they carry sediment from the melting glacier. This sediment is deposited at the terminus of the glacier in an area called the **outwash plain**. These areas, particularly those at the terminus of continental glaciers, contain an abundance of additional landforms (**Figure 19.20**). For example, large blocks of ice can be left behind on the plain to melt creating a depression called a **kettle** that can be later filled with surface water like a **kettle lake**.

As glaciers melt, the meltwater flows over the ice surface until it descends into crevasses, finding channels within the ice or continuing to the base of the glacier into channels along the bottom. Such streams located under continental glaciers carry sediment in a sinuous channel within or under the ice, like a river. When the ice recedes, the sediment remains as a long sinuous ridge known as an **esker** (**Figure 19.20**).

Meltwater descending through the ice or along the margins of the ice may deposit mounds of sediment that remain as hills called **kames** (**Figure 19.20**). The meltwater that forms eskers and kames results in these landforms being composed of sediment (**stratified drift**), which is layered, sorted, and more rounded than till.

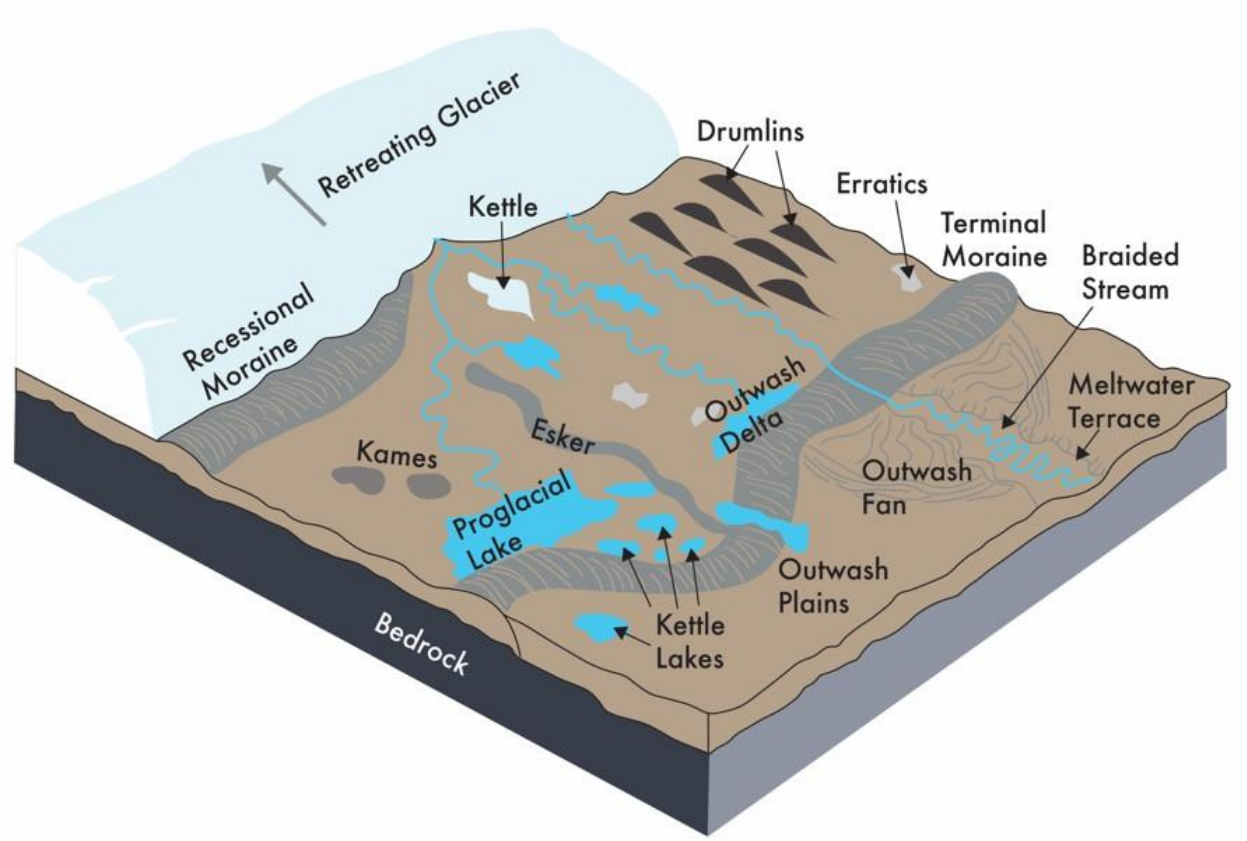


Figure 19.20: Continental ice sheet landforms, including outwash features, kettles and kettle lakes, eskers, kames, drumlins, and moraines.

Other landforms typical of the outwash plain include **drumlins**, elongated teardrop-shaped hills. Drumlins form with their steepest side pointing upstream to the flow of ice and streamlined side (low angle side) pointing in the direction the ice is flowing (**Figure 19.21**). Vast quantities of drumlins occur in **drumlin fields,** common in the US in places like New York, Wisconsin and Minnesota. The origin of drumlins is still unknown; however, leading ideas suggest incremental accumulation of till under the glacier, large catastrophic meltwater floods beneath the glacier, or surface deformation by the weight of the overlying glacial ice.

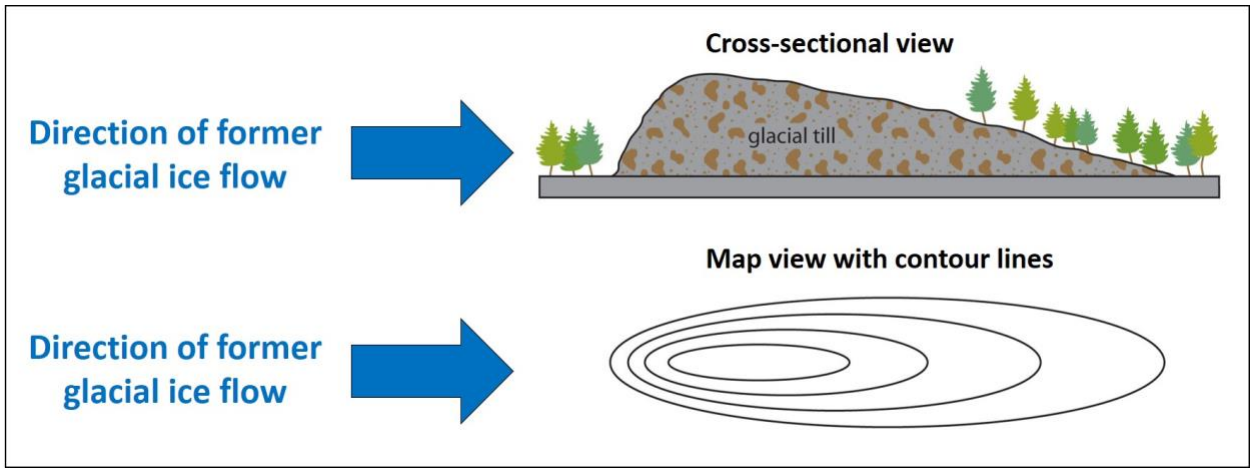


Figure 19.21: Drumlin formation. Note the glacial flow direction versus resulting topography.

Attributions

- Figure 19.18: Derivative of “Glacial Features” (Public Domain; Trista L. Thornberry-Ehrlich, Colorado State University/NPS via Flickr) by Chloe Branciforte
- Figure 19.19: Derivative of “Baldwin and Fraser Glaciers Confluence” (Public Domain; Jacob W. Frank/NPS via Flickr) by Chloe Branciforte
- Figure 19.20: “Continental Ice Sheet Landforms” (CC-BY 4.0; Emily Haddad, own work)
- Figure 19.21: Derivative of “Drumlin & Roche Moutonnée” (Public Domain; Trista L. Thornberry-Ehrlich, Colorado State University/NPS via Flickr) by Chloe Branciforte

Glacial Erosional Landforms

The sediment carried glacial ice and subglacial runoff is responsible for the majority of the erosion of glacial environments. As we saw above, the sediment grinds, carves, and polishes the bedrock surface.

Continental glaciers act as bulldozers, and as a result produce uniformly subdued topography. Valley glaciers, on the other hand, are confined by their topography and typically produce distinct erosional features, visible once the glacier recedes (**Figure 19.22**): for example, **glacial troughs or U-shaped valleys**, and, in coastally glaciated areas, **fjords** (submerged glacial valleys). Between two adjacent U-shaped valleys you will typically find a ridge called an **arête**. At the head of a valley glacier there is often a **cirque**, a bowl-shaped feature where the head of the glacier is eroding against the mountain by plucking rock away.

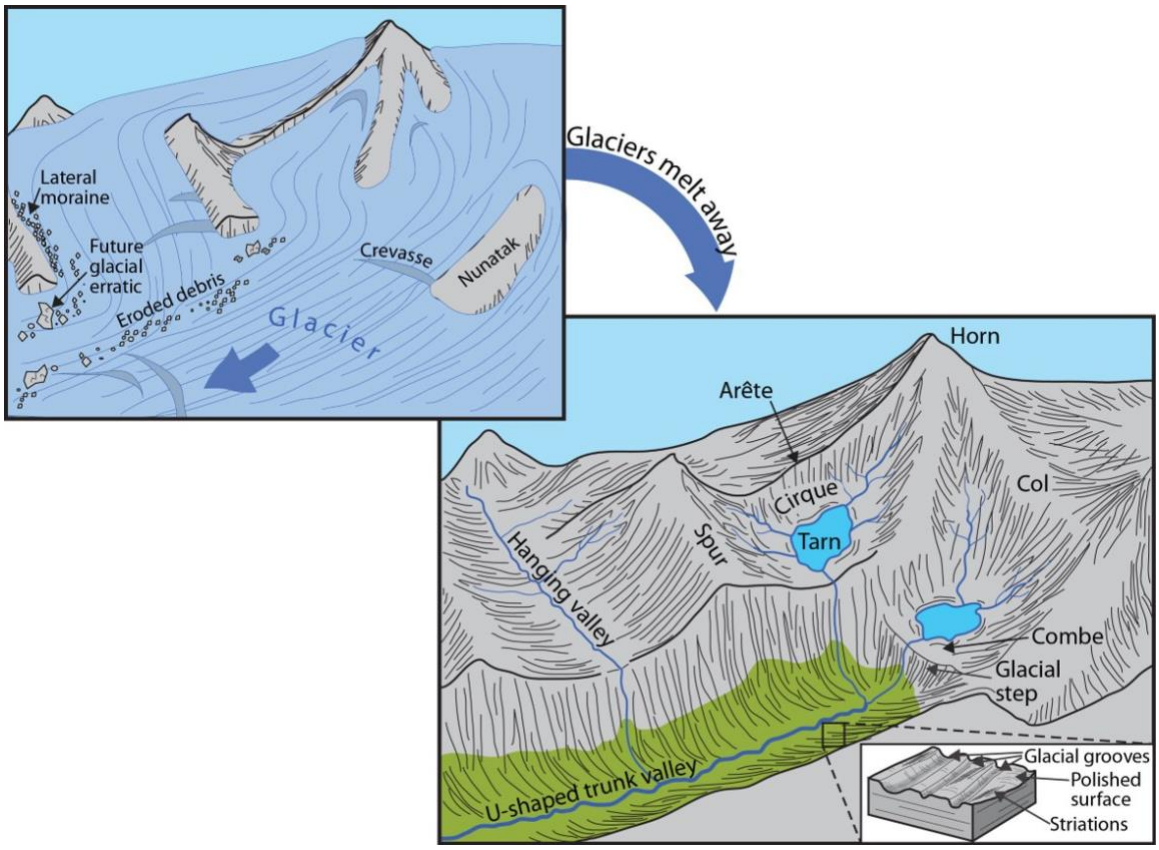


Figure 19.22: "Classic" landforms which are common to areas that were glaciated.

After the glacier is gone, the bowl at the bottom of the cirque can be occupied by a **tarn lake**. Headward cirque erosion by three or more mountain glaciers produces **glacial horns**, steep-sided, pyramid-shaped mountains. Low points along arêtes or between horns are termed **cols,** or mountain passes. Smaller tributary glaciers can intersect larger glaciers, and, after the ice

recedes, the tributary valley becomes a **hanging valley**, sometimes with a waterfall, like Bridalveil Falls in Yosemite National Park (**Figure 19.23**).

Figure 19.23: Bridalveil Falls in Yosemite National Park cascades over a hanging valley.

Lastly, **roche moutonnée** (or sheepback) are bedrock formations that are produced when the glacial ice abrades and plucks the underlying bedrock into an asymmetric form (**Figure 19.24**).

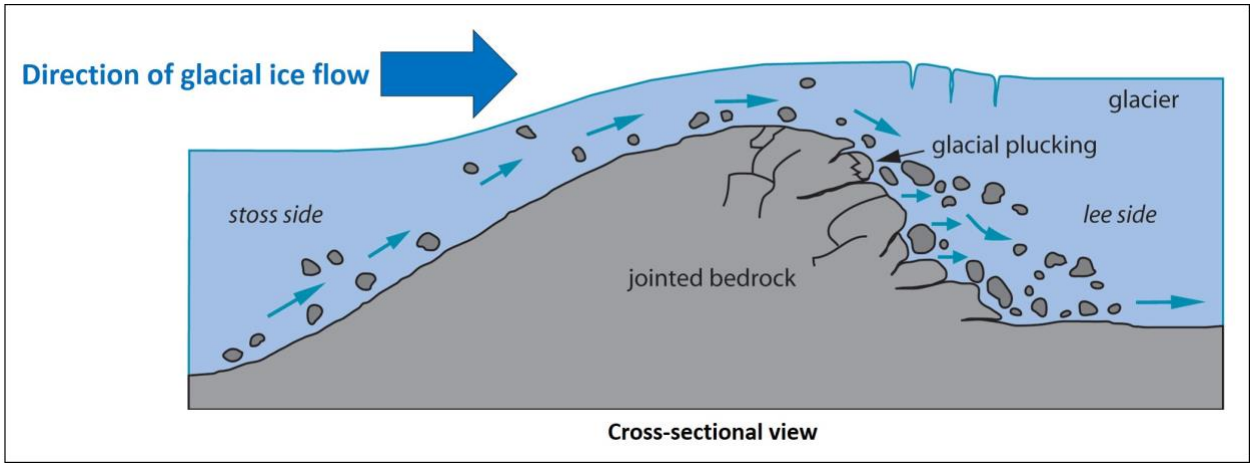


Figure 19.24: Roche moutonnée formation; note the glacial flow direction versus resulting topography.

Lakes are common features in glacial environments. In addition to the tarn lakes of valley glaciers, there may be a series of lakes, called **paternoster lakes**, which can develop when recessional moraines isolate multiple basins within a glaciated valley. Common in both valley and continental glaciated areas, elongated lakes may occupy glacially carved depressions, known as **finger lakes**, the most famous being the aptly named Finger Lakes of central New York (**Figure 19.25**). In areas of continental glaciation, the crust is depressed isostatically by crustal loading from the weight of thick glacial ice. Basins are formed along the edges these continental glaciers will fill with meltwater and form **proglacial lakes** (**Figure 19.20**). These glacial lakes often have unique sediment deposition, including **glacial varves**, which represent seasonal sediment accumulation.

Figure 19.25: NASA imagery of New York's Finger Lakes, a region of steep, roughly parallel valleys and hills shaped by advancing and retreating ice sheets that were as much as 2 miles deep during the last ice age (2 million years to about 10,000 years ago). Inset shows Taughannock Falls near Cayuga Lake (location indicated by blue star) cascading over a hanging valley.

Attributions

- Figure 19.22: “All Things Glacial” (Public Domain; Trista L. Thornberry-Ehrlich, Colorado State University/NPS via Flickr) by Chloe Branciforte
- Figure 19.23: "Bridalveil Falls, Yosemite" (CC-BY 3.0; Asamudra via Wikimedia Commons)
- Figure 19.24: Derivative of “Drumlin & Roche Moutonnée” (Public Domain; Trista L. Thornberry-Ehrlich, Colorado State University/NPS via Flickr) by Chloe Branciforte
- Figure 19.25: Derivative of "New York's Finger Lakes" (Public Domain; NASA) by Emily Haddad

Activity 19A: Yosemite National Park and Glacial Landforms

1. Using the **browser version of Google Earth**, fly to Yosemite Valley, 37°44'35.8"N, 119°35'33.7"W. In the bottom right corner of the Google Earth screen you'll see a button that says 2D; if you click it you will change your view to 3D. Ensure the button says 2D. Use the compass feature to navigate Yosemite Valley, you'll be able to examine from all angles. What type of glacier likely formed Yosemite Valley? Why do you think that?

2. Using the **browser version of Google Earth**, fly to Mt. Lyell, 37°44'24.0"N 119°16'12.0"W and zoom to an eye altitude (Camera) of 22,000 feet. Switch between 2D and 3D to see the landscape at different angles. Mt. Lyell is the highest point in Yosemite NP and is home to the Lyell Glacier. Which major erosional landforms do you immediately observe?

3. Using the **browser version of Google Earth**, fly to Spiller Lake, 38°02'49.9"N 119°22'06.1"W and zoom to an eye altitude (Camera) of 15,700 feet.
    a. What is this glacial lake called?
    b. What erosional feature does the lake sit in?

4. Using the **browser version of Google Earth**, fly to 37°52'54.3"N, 119°20'47.7"W and zoom to an eye altitude of 11,000 feet.
    a. What is this erosional landform?
    b. What information can we interpret from this landform?

5. Using the **browser version of Google Earth**, fly to 37°42'58.2"N, 119°38'45.7"W and zoom to an eye altitude of 7,000 feet.
    a. What is this erosional landform?
    b. How can you tell?

6. Identify the name of the glacial sediment represented in **Figure 19.26** below.

Figure 19.26: Sediment for Question 6 in Activity 19A.

7. Watch this video from the National Park Service on the glaciers of Yosemite National Park.
    a. In your opinion, what was interesting about the Maclure Glacier?

Attributions

- Figure 19.26: “Angular Boulder on Lambert Dome” (CC-BY 3.0; Daniel Mayer via Wikimedia Commons)

Activity 19B: Identifying Continental Glacier Landforms

1. Identify the depositional glacial landforms on the topographic map below.
    a. What type of glacier likely formed these landforms? Why?

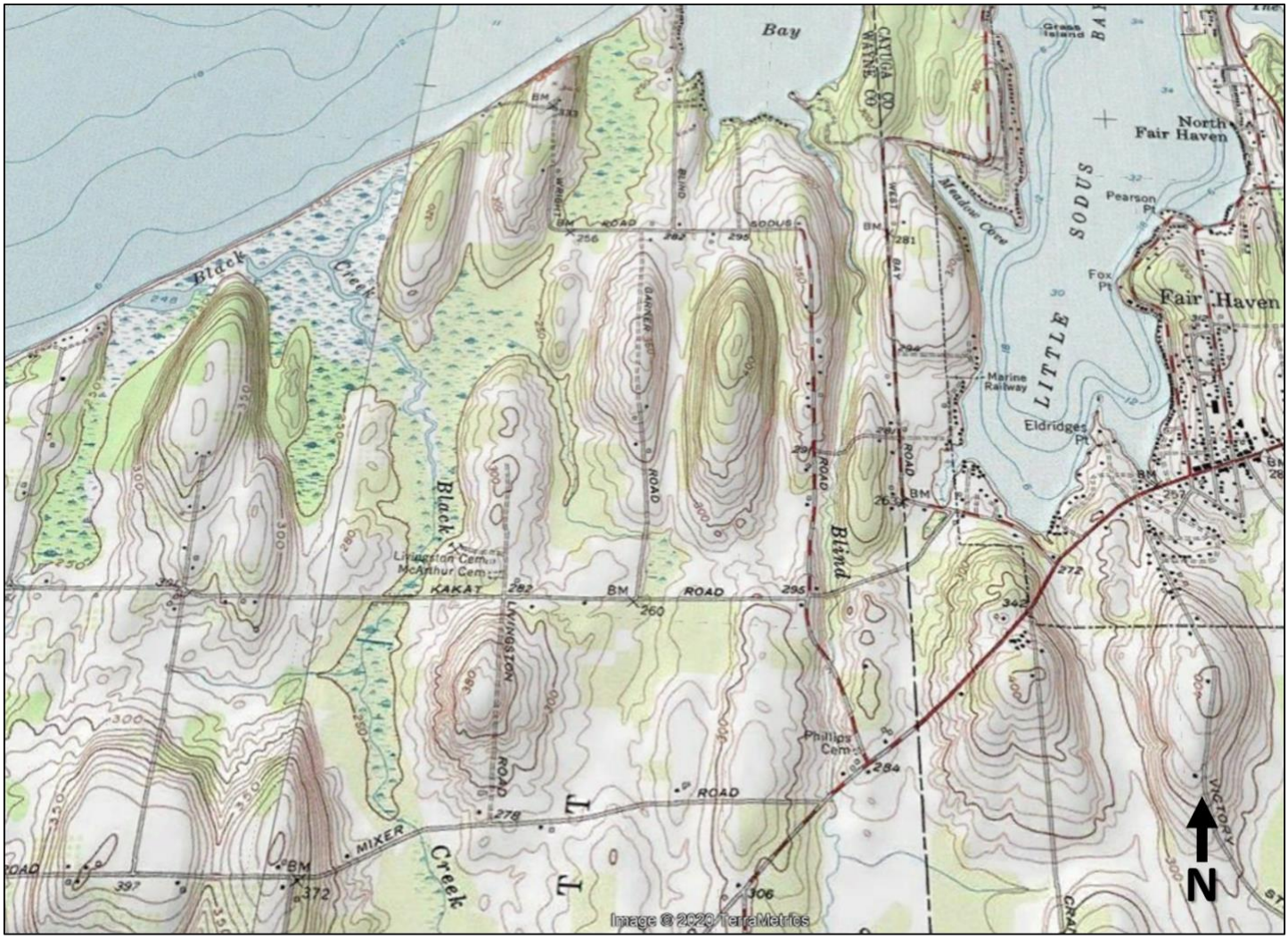


Figure 19.27: Landforms for Question 1 in Activity 19B.

2. What type of moraine is pictured at the yellow arrow below?

Figure 19.28: Moraine for Question 2 in Activity 19B.

3. Which types of moraines are pictured below?

a. At A:

b. At B:

Figure 19.29: Moraines for Question 3 in Activity 19B.

Attributions

- Figure 19.27: “Continental Glacier Landforms” (CC-BY 4.0; Chloe Branciforte via Earth Point)
- Figure 19.28: “060727-693” (CC-BY 2.0; USFS via Flickr)
- Figure 19.29: “060727-693” (CC-BY 2.0; USFS via Flickr)

Chapter 20: Climate Change

Learning Outcomes

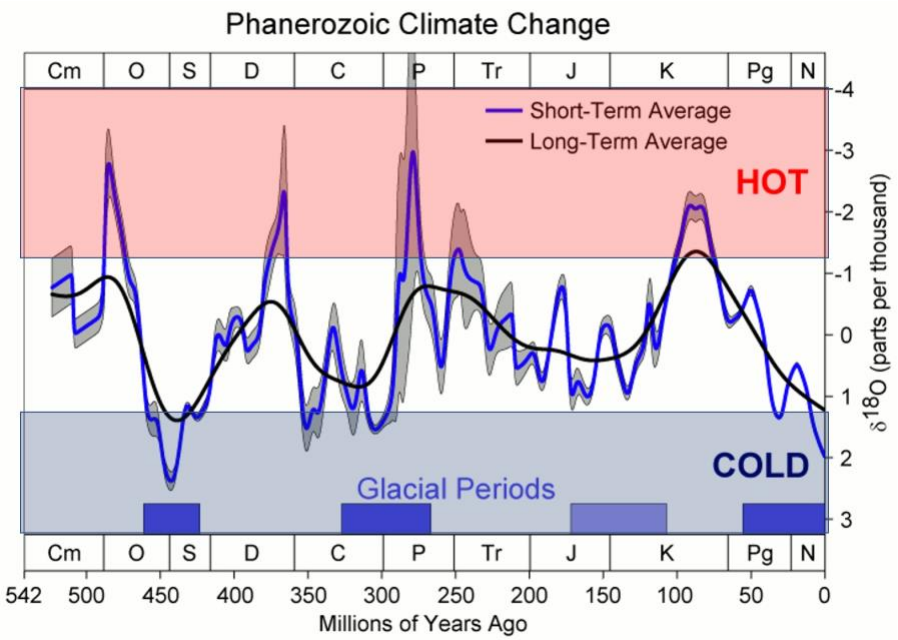
After completing this chapter, you should be able to:

✓ Discuss and give examples of both positive and negative feedback loops.

✓ Plot, interpret, and explain the patterns in climate data.

✓ Describe the impacts of climate change in California.

Thumbnail for Chapter 20:



Thumbnail: Derivative of "Phanerozoic Climate Change" (CC-BY-SA 3.0; Global Warming Art via Wikipedia) by Chloe Branciforte

What Is the Climate System?

Recall that climate is the long-term weather pattern across a region. It is important to emphasize the "long-term" portion of the definition to establish that ***climate is different from weather*** (Figure 20.1). Weather is the local and short-term patterns in temperature, humidity, precipitation, atmospheric pressure, wind, and other meteorological variables. Weather fluctuates throughout the day, week, month, and year such that it is difficult to see trends beyond the random noise in the system. If you examine weather over the long-term, we can begin to see patterns across time and geography that help to better understand and identify the factors that influence the climate system.

Figure 20.1: Here's one way to visualize it: Weather tells you what to wear each day; climate tells you what types of clothes to have in your closet.

The climate system is the interconnected network of variables that influence the earth's climate, which includes components from the five Earth spheres (geosphere, atmosphere, hydrosphere, cryosphere, biosphere, including humans), and the **exosphere** (beyond our

planet). It is important to distinguish humans from other life for several reasons, primarily because many of our activities are unique amongst life (including **industrialization**) and it clarifies our role in climate change. The science responsible for examining past, current, and future climate is incredibly complex and interdisciplinary. The history of climate is recorded within rocks, sediments, fossils ,and ice, and climate can be altered by geologic events and influenced by our use of geological resources such as **fossil fuels**. Climate science is essential to understanding the dynamics and implications of future climate change, as well as attempting to combat or **mitigate** the potential effects.

The science behind climate change is robust and well-studied; there is consensus within the scientific community regarding the impact of humans on climate. The data demonstrate that humans are warming the climate at a rate faster than Earth has experienced in the last 55 million years. Unfortunately, within the broader population there are still many who deny the impact of humans on climate. This is likely related to factors beyond science, including economics, politics, the portrayal of science by the media, and the public's overall scientific literacy. Here in California, regardless of your location, you have likely already experienced the effects of a changing climate. During the last decade, we have seen much of the state plagued by severe droughts and an increased number and intensity of wildfires, coastal communities are combating rising sea-level, and the snowpack of the Sierra Nevadas have become significantly reduced, affecting the water supply for 23,000,000 Californians.

A person who studies climate or climate science is typically referred to as a climatologist or climate scientist. However, there are many categories of climate scientists, many of which study climate through the different Earth spheres. For example, glaciologists, sedimentologists, oceanographers, and even paleontologists can be climate scientists. Each branch uniquely investigates Earth's climate through time by studying ice cores, marine sediment cores, or rocks and fossils. Like many other geoscientists, working with other disciplines is common, with a heavy influence from both math and technology. Many are employed by universities where they teach and/or do research, and state and federal agencies, including geological surveys, like the California Geological Survey or United State Geological Survey (USGS). Additional career pathways include environmental policy and legislation and consulting, or science communication via the private sector or state and federal agencies. Many of these career options require a college degree and postgraduate work. If you are interested in climate science talk to your geology instructor for advice. We recommend completing as many math and science courses as possible. Also, visit National Parks, CA State Parks, museums, gem & mineral shows, or join a local rock and mineral club. Typically, natural history museums will have wonderful displays of rocks, including those from your local region. Here in California, there are a number of large collections, including the San Diego Natural History Museum, Natural History

Museum of Los Angeles County, Santa Barbara Museum of Natural History, and Kimball Natural History Museum. Many colleges and universities also have their own collections/museums.

Many people are often overwhelmed with the impacts of climate change and ask "but what can I do?" Change can begin in your own communities: use the EPAs carbon footprint calculator and see what you can start doing differently today. Support public officials who stand with science and are willing to adapt and formulate plans of action by voting. Begin a Climate Change club at your college and engage with the community and local organizations who advocate for **environmental justice**. For more ways to reduce your impact on the environment, read this article from the Earth Institute at Columbia University.

Attributions

- Figure 20.1: “Weather vs. Climate” (Public Domain; NOAA)

How Is Heat Transferred within the Climate System?

The heat that feeds the climate system comes from two primary sources. The first source is internal to earth, the heat radiating from the Earth itself. This heat is primarily from the decay of radioactive material and residual heat from the formation of earth. This heat is not distributed equally, with more heat escaping in areas where the crust is thinner, such as **divergent boundaries**. The second, and more significant source, is the heat Earth receives from **solar radiation**. Again, this heat is not distributed equally across the earth's surface. The amount of energy received is related to the angle at which the sun's rays hit the surface. Overall, these angle differences create the large climate differences across Earth. For example, at the equator solar radiation is received perpendicular to the surface which causes more heat to be absorbed per square foot. Conversely, at the poles, solar radiation is received parallel or at an oblique angle, which results in less heat absorption; therefore, the tropics are much warmer than the poles. (**Figure 20.2**).

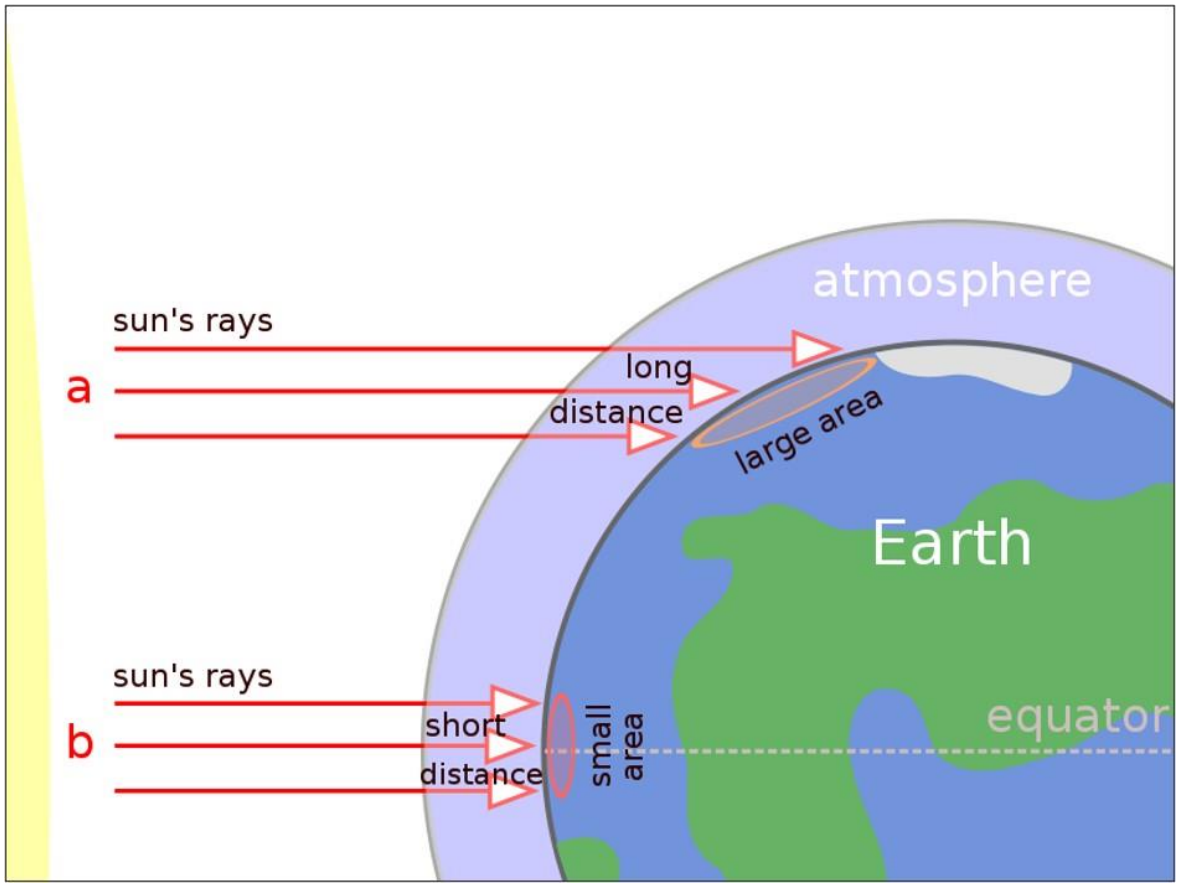


Figure 20.2: Why are the polar regions colder? Both Poles are cold because they do not receive any direct sunlight. The Sun is always low on the horizon, even in the middle of summer. In winter, the Sun is so far below the horizon that it doesn't come up at all for months at a time.

Attributions

- Figure 20.2: “Oblique Rays 02 Pengo” (CC-BY-SA 2.5; Peter Halasz via Wikimedia Commons)

The Albedo Effect

While the angle and amount of incoming solar radiation (**insolation**) is the most important determinant of Earth's climate, the material on the Earth's surface is also important, as not all materials will react the same to solar radiation. For example, darker colored materials, like the ocean, absorb and reradiate heat, most of which is retained at the surface of the planet. You are likely familiar with this if you have ever walked barefoot on dark concrete or asphalt in the summer. Lighter colored materials, like ice and snow, reflect solar radiation off the Earth's surface. This is the reason many skiers and glacial scientists use eye protection to avoid snow blindness.

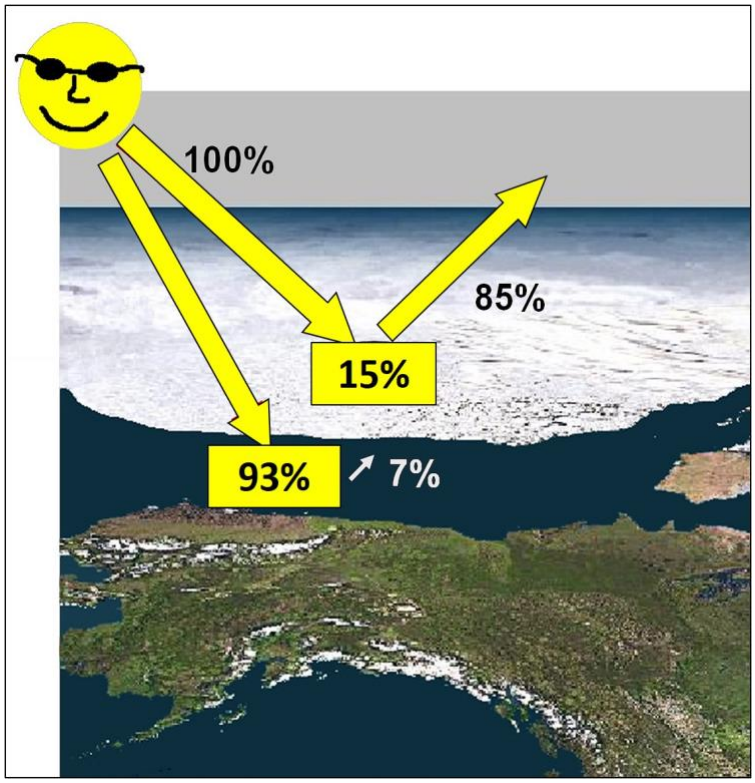


Figure 20.3: Sea ice reflects as much as 85% of solar radiation hitting the surface therefore absorbing only 15%. Ocean water reflects only about 7% of solar radiation and absorbing 93%.

The proportion of solar radiation that is reflected off the Earth's surface is called **albedo**, which varies depending on the type of ground cover (**Figure 20.3**). Earth's albedo is higher when it is covered with large expanses of glacial ice and therefore both the amount of sunlight absorbed and the temperature are lower. The distribution of water, ice, snow, vegetation, and other materials on the Earth's surface control the Earth's albedo and can change over time.

Attributions

- Figure 20.3: “Derivative of “Ice Albedo” (Public Domain; Don Perovich Cold Regions Research and Engineering Laboratory (CRREL)/NOAA via Flickr) by Chloe Branciforte

The Exosphere and Climate Change

Many factors external to Earth influence the climate system. These include the amount of radiation produced from the sun as it varies over time, the overall shape of our orbit around the sun varies over time, and the angle at which solar radiation hits the planets' surface. Over a century ago, Serbian scientist Milutin Milankovitch hypothesized the long-term, collective effects of changes in Earth's position relative to the Sun were a strong driver of Earth's long-term climate and responsible for triggering the beginning and end of **glacial periods** (Ice Ages). Milankovitch determined that over time, Earth's placement in space affects the amount of radiation received from the sun. Collectively, his ideas are known as the **Milankovitch Cycles** and include the following patterns of motion.

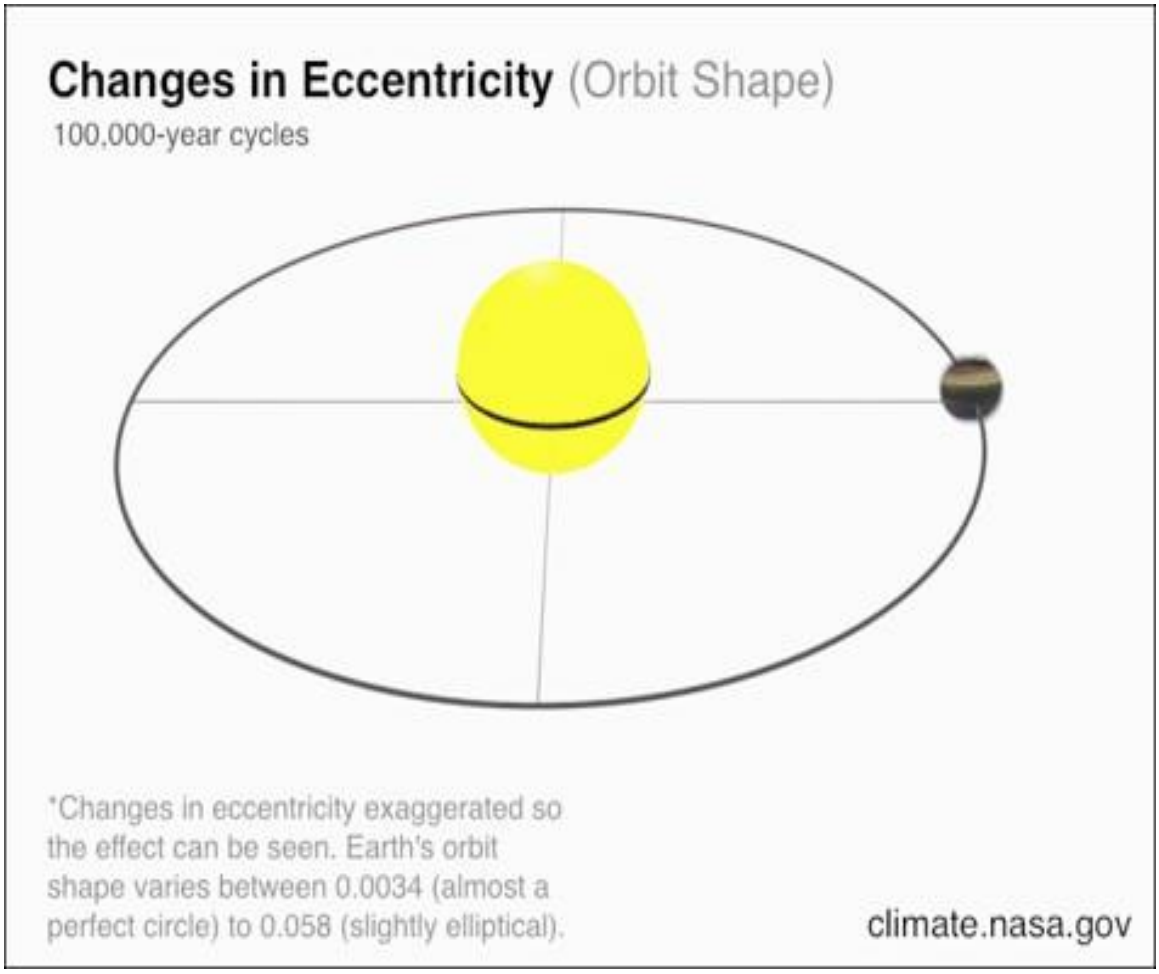


Figure 20.4: Eccentricity: orbit shape.

Eccentricity, the overall shape of Earth's orbit around the Sun, alternates between more circular and more elliptical in a cycle that spans about 100,000 years, in part due to the gravitational influence of the gas giants, Jupiter and Saturn. Currently, Earth's eccentricity is

near its least elliptic (i.e. most circular) and is very slowly decreasing (**Figure 20.4**). For GIFS visit this NASA page.

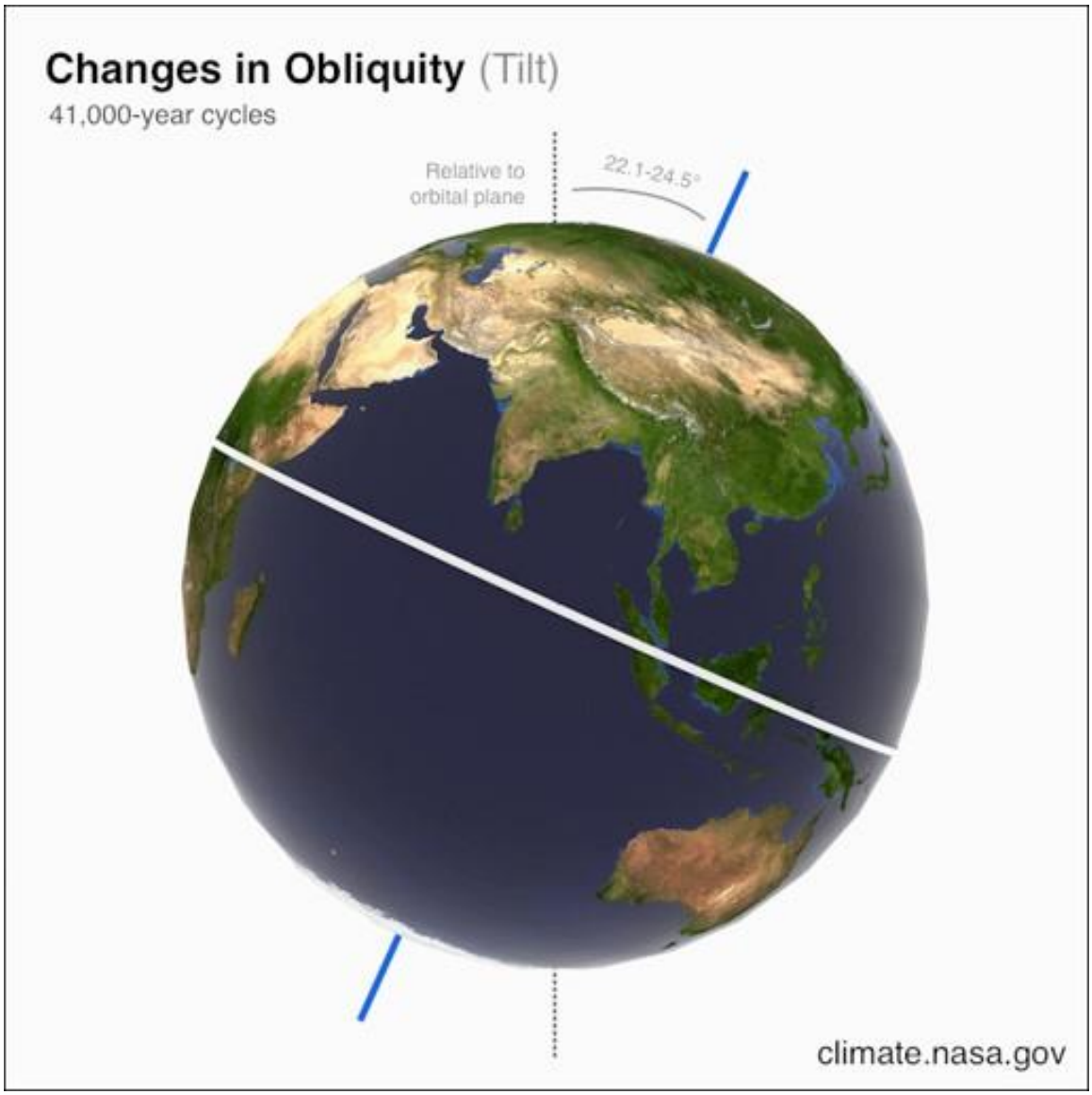


Figure 20.5: Obliquity: axial tilt.

Obliquity is the angle of Earth's axis of rotation relative to its ecliptic plane around the Sun. Obliquity is the reason Earth has seasons and is a very strong control on Earth's climate and glacial periods. Typically, Earth's obliquity varies between 22.1 and 24.5 degrees in a cycle that spans about 41,000 years, with minimum tilt favoring glaciation and maximum tilt promoting interglacial periods. Earth's axis is currently tilted 23.4 degrees and is very slowly decreasing towards minimum tilt (**Figure 20.5**). For GIFS visit this NASA page.

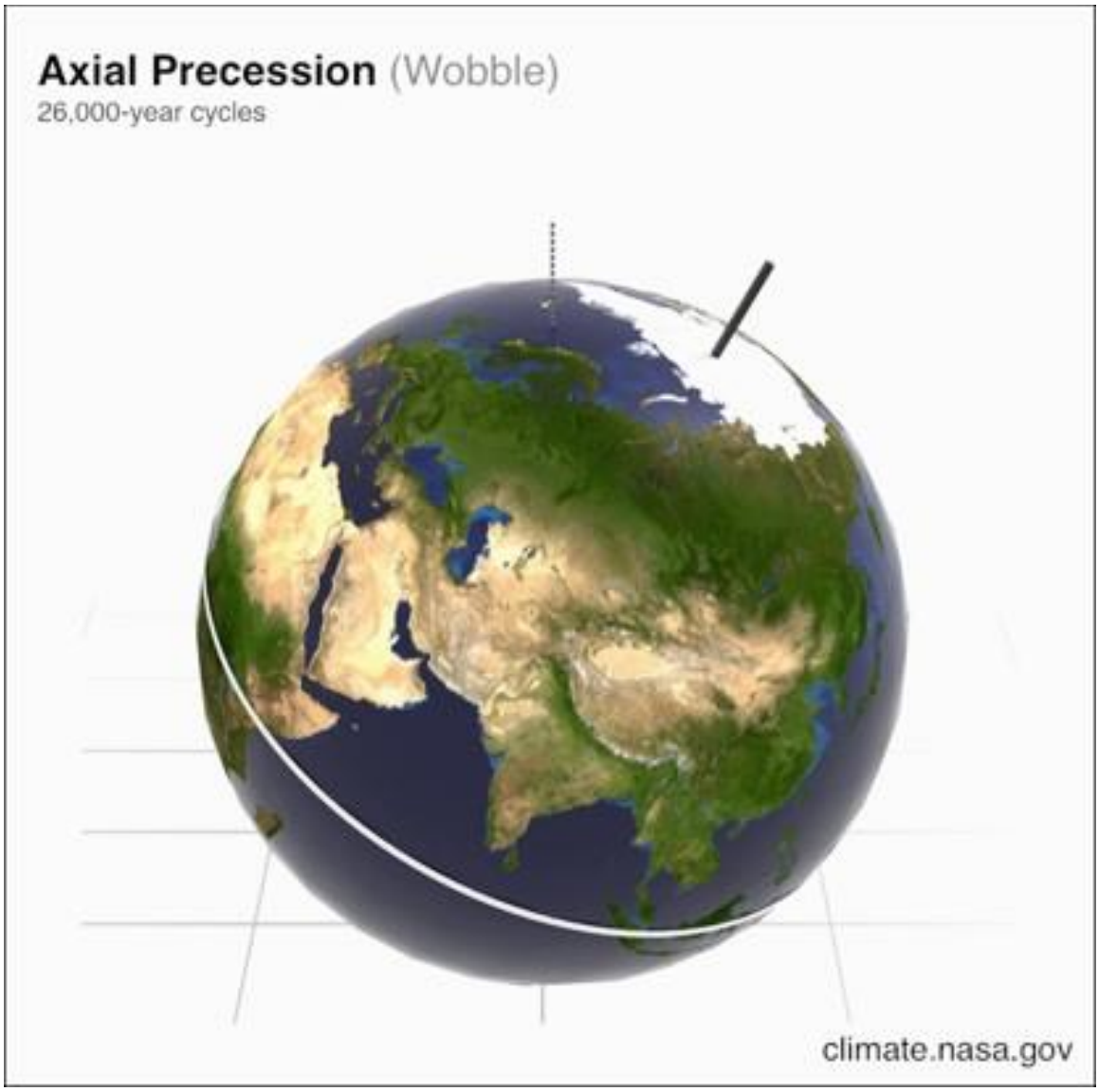


Figure 20.6: Axial precession: wobble.

Precession is the slight wobble of Earth as it rotates on its axis. This wobble is due to tidal forces caused by the gravitational influences of the Sun and Moon. The direction of wobble is determined relative to the fixed positions of stars; Earth is currently fixed to Polaris in the northern hemisphere but may wobble toward other North Stars, including Thuban and Kochab. The cycle of axial precession spans about 25,000 years (**Figure 20.6**). For GIFS visit this NASA page.

When the cycles occur together at the same interval, they can influence Earth's climate, and with other factors in place may encourage a **glacial period or glaciation** to occur.

Attributions

- Figure 20.4: “Milankovitch (Orbital) Cycles and Their Role in Climate” (Public Domain; NASA)
- Figure 20.5: “Milankovitch (Orbital) Cycles and Their Role in Climate” (Public Domain; NASA)
- Figure 20.6: “Milankovitch (Orbital) Cycles and Their Role in Climate” (Public Domain; NASA)

The Atmosphere and Climate Change

Once heat radiates off Earth's surface it travels into the atmosphere. Certain gases in Earth's atmosphere, called **greenhouse gases**, allow sunlight to pass but absorb terrestrial energy and radiate it in all directions, including back to the surface of the Earth (**Figure 20.7**).

Figure 20.7: A simplified animation of the greenhouse effect.

These gases, such as water vapor, carbon dioxide, ozone, and methane, represent a tiny but important fraction of atmospheric material. Different greenhouse gases vary in how effectively they absorb and reradiate energy and in their relative proportions in the atmosphere; a higher concentration of potent greenhouse gases can retain more thermal energy within the atmosphere while the rest of the reflected and radiated energy escapes from the atmosphere and dissipates into space. The proportion of greenhouse gases in the atmosphere has changed dramatically through geologic time as a result of numerous factors influencing the atmospheric system, including the rate of plate motion, amount of volcanism, photosynthesis, weathering of rocks, burning of fossil fuels, and more.

Another major component of our atmosphere are **aerosols** (sea spray, dust, ash, etc.). Aerosols originate from surficial processes, like the expulsion of ash or sulfur dioxide from volcanoes and the burning of fossil fuels, that can alter climate by reflecting incoming solar radiation before it reaches the Earth's surface.

Attributions

- Figure 20.7: “The Causes of Climate Change” (Public Domain; NASA/JPL-Caltech)

The Oceans and Climate Change

The oceans influence the weather on local to global scales, while changes in climate can fundamentally alter many properties of the oceans. Heat is transported across the Earth's surface through wind currents, storms, and ocean currents (**Figure 20.8**). Large circular ocean currents, called **gyres**, appear to have a significant impact on the geographic distribution of heat on Earth and large-scale climate change in Earth's history. These currents are particularly effective in melting polar ice as they melt the sea ice from below.

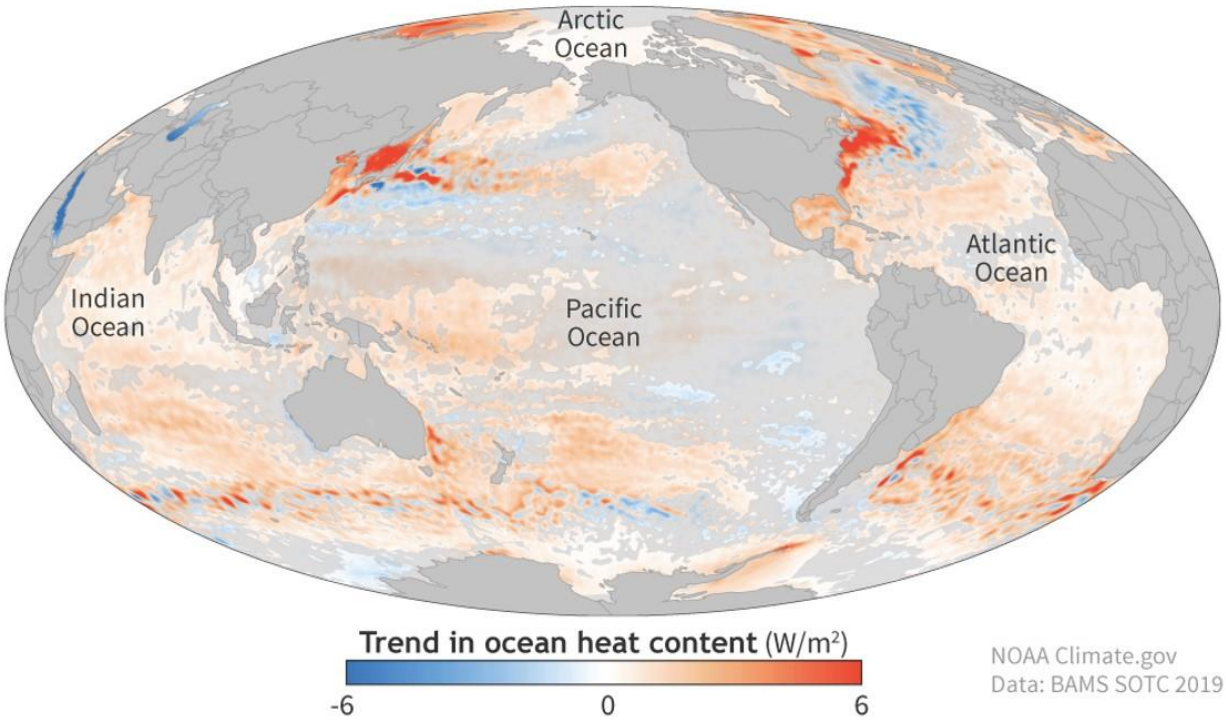


Figure 20.8: This map of heat content trends in the upper 700 meters (2,300 feet) of the world ocean shows where the oceans gained or lost heat between 1993 and 2019. Large parts of most ocean basins are gaining heat (orange)—and the global average trend is positive – but some areas have lost heat. Places with gray shading have trends that are not statistically significant.

More than 90% of the warming that has happened on Earth over the past 50 years has occurred in the ocean. Ocean heat content not only determines sea surface temperature, but also affects sea level and currents. Scientists have determined that global sea level has been steadily rising since 1900 at a rate of at least 0.04 to 0.1 inches per year. Sea level can rise by two different mechanisms with respect to climate change: 1) as the oceans warm due to an increasing global temperature, seawater expands, taking up more space in the ocean basin and causing a rise in water level, and 2) as ice melts on land and drains to the ocean, increased volume of water in

the ocean basin causes a rise in sea level. Rising sea-level has major implications for our coastal states and communities, including flooding and the way we manage our coastal resources.

Lastly, the oceans absorb 30% of atmospheric carbon dioxide. As these carbon dioxide levels rise and more is absorbed by the oceans, the average pH of the ocean changes, a process called **ocean acidification**. The higher acidity affects the balance of minerals, like calcite and aragonite, in the water, which can make it more difficult for certain marine animals to build their skeletons or shells.

Attributions

- Figure 20.8: “Change in Ocean Heat Content (1993-2019)” (Public Domain; NOAA/Climate.gov, via State of the Climate (2019))

The Cryosphere and Climate Change

The extent of **sea ice** coverage on the North and South Polar ice sheets is easy to assess from satellite images and is measured as the size of the ice sheet in million square kilometers (**Figure 20.9**). Sea ice extent is not a perfect indicator of global climate change, but it is easy to understand that a warming of the Earth is likely to cause a decrease in the amount of ice at the poles and thus a decrease in the **sea ice extent**, while a cooling event will cause an increase in ice production.

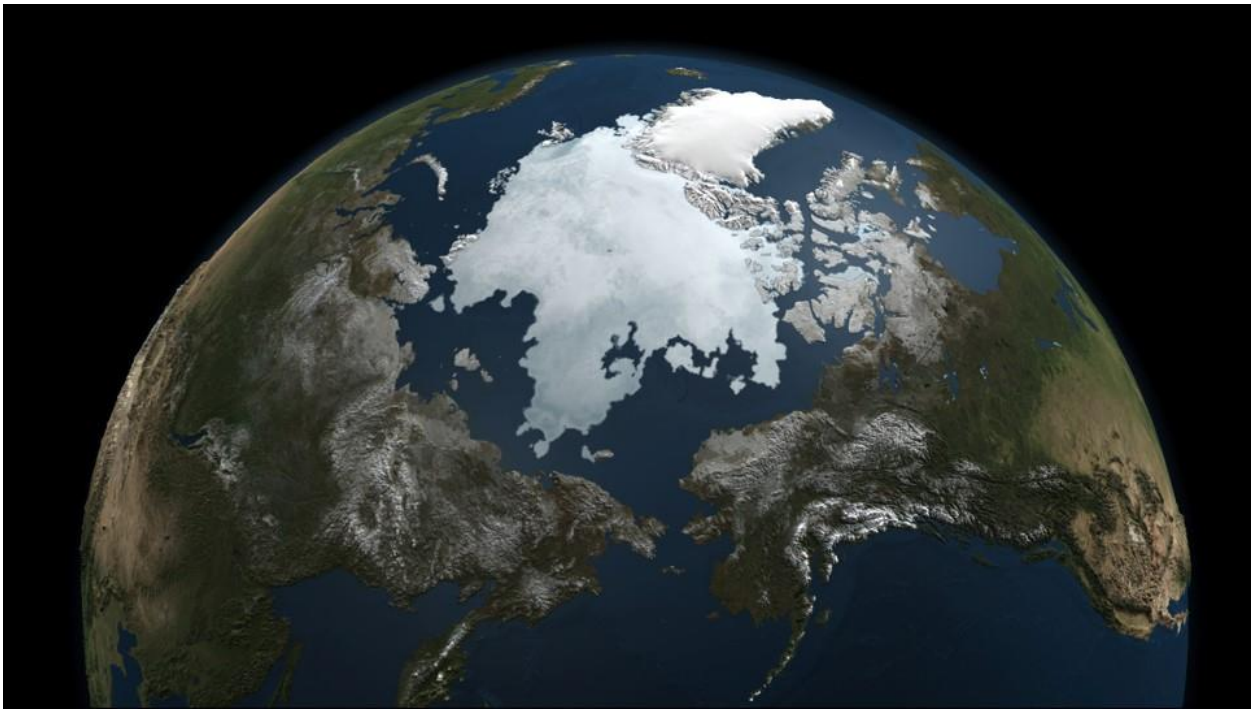


Figure 20.9: The Arctic Ocean is covered by a dynamic layer of sea ice that grows each winter and shrinks each summer, reaching its yearly minimum size each fall.

Attributions

- Figure 20.9: “A Snapshot of Sea Ice” (CC-BY 2.0; NASA/Goddard Space Flight Center Scientific Visualization Studio via Flickr)

Climate Feedback Loops

Based on the number of variables and how they change over time, it is readily apparent how complex and interconnected the climate system is. For instance, when a volcano erupts, it 1) adds some thermal energy to the climate system, 2) produces aerosols that block solar radiation from hitting the Earth's surface, and 3) produces greenhouse gases that retain heat. Notice that these factors do not influence climate in a consistent way. The change of one variable as the result of another is called **feedback**, which can be positive (reinforcing) or negative (discouraging). For climate, a feedback that increases an initial warming is called a **positive feedback** whereas a feedback that reduces an initial warming is a **negative feedback**.

Positive feedback loops enhance or amplify changes, moving the system away from equilibrium. For instance, if Earth warms, ice melts and reduces albedo, which results in additional warming. This can also occur in the opposite direction: if Earth cools, ice forms and increases albedo, which results in additional cooling.

Negative feedback loops dampen or buffer changes, holding a system to some equilibrium state and making it more stable. For instance, if the Earth warms, more surface area becomes arid, resulting in an increase in the amount of dust in the atmosphere, which reflects solar radiation, causing cooling. Again, the opposite works: if the Earth cools, less surface area is arid, resulting in a decrease in the amount of dust in the atmosphere, which causes warming.

Understanding the climate system requires identifying all significant climate variables, how they are related to each other, the speed at which they can change, and the magnitude and direction of change for each feedback loop. The best way to gain a better understanding of the climate system is to study it through geologic history.

Climate Proxies and the Climate Record

For many of us, the most obvious method to study climate would be to record it directly. For example, we could use a thermometer to directly measure air temperature; however, thermometers only provide a localized measurement, and more importantly, they are a relatively recent invention. How do we measure the temperature of the Cretaceous, Permian or Devonian atmospheres or oceans? Direct observations do not give us the long-term trends we need to establish climate change patterns; instead, we must look at a natural recorder of climate called a **climate proxy**. As climate changes, it affects the deposition of sedimentary rock, rock chemistry, and fossil organism, all of which can be studied by geoscientists to reconstruct ancient climate patterns in a field called **paleoclimatology**.

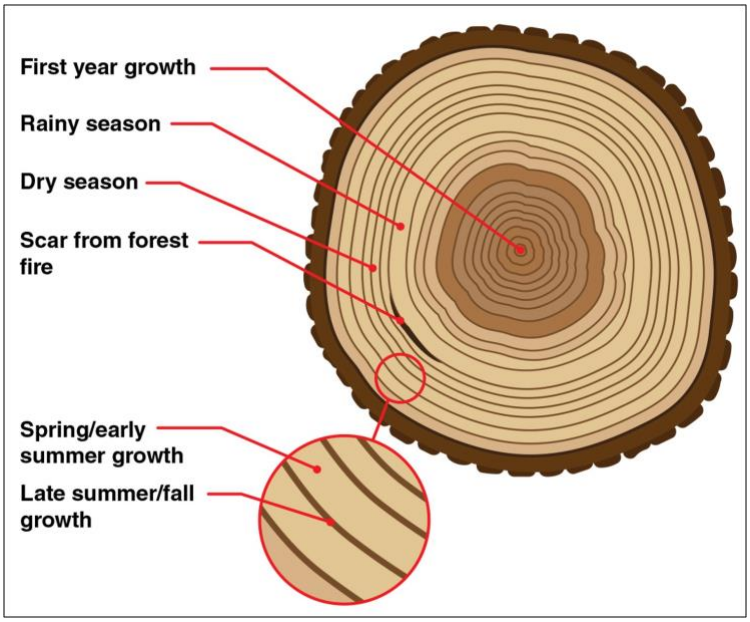


Figure 20.10: The color and width of tree rings can provide insight into past climate conditions.

An individual climate proxy may not provide a clear signal of global climate for a couple of reasons: 1) proxies show a history of the area in which they were formed, not of an entire region, 2) an individual proxy, which may have a long or a short record, can record the short-term variability of weather events, and 3) most climate proxies are influenced by multiple factors. For instance, the thickness of tree rings, **dendrochronology**, is a wonderful proxy for temperature. Trees grow more in warmer years, producing thicker rings, and less in colder years, producing thinner rings; however, a tree could also grow slowly because of a drought or because of an infestation of pests even if it was a warm year (**Figure 20.10**).

If all individual proxies show local patterns, with some degree of weather-related noise, and possibly influenced by other factors, how can we reconstruct long-term global temperature records? The answer lies in increasing the size of the dataset. If temperature is the most important variable influencing the proxies, and we combine hundreds to thousands of individual proxy records, an overarching pattern emerges. Again, an individual proxy record may be contrary to the overall trend, but that is to be expected since a local region can have a cold winter during an overall hot year for the planet. To illustrate this, consider the following:

say we want to reconstruct overall economic patterns over the past few hundred years in the United States of America. We could examine lots of proxies for economic growth, like employment, the stock market, individual wealth, or rates of home ownership. If we only looked at one of these proxies, we likely would not get a clear picture of change. Also, if we only looked at Los Angeles, California, for example, we would be unlikely to see a trend that mimics the entire country. Again, the more data we have, whether for climate or any other complex system, the clearer the signal becomes over the local and random noise.

One of the most commonly used climate proxies is the measurement of **oxygen isotopes**. As you may remember, **isotopes** are atoms of the same element that differ in their masses because of differences in the number of neutrons in the nucleus of the atom. Multiple isotopes of oxygen are stable, meaning they do not radioactively decay over time. Oxygen has two stable isotopes that occur in a constant ratio on Earth; however, certain minerals, like calcite or ice, prefer one isotope over the other within their crystal structure. This preference results in a ratio of oxygen isotopes that is different from the ratio found in other materials; this difference is called **fractionation**. The amount of fractionation in oxygen isotopes is temperature dependent, such that the mineral calcite has a different ratio of oxygen isotopes if it was formed in near-freezing versus warm water. Oxygen isotopes provide climate records from many different sources, including coral, clams and other mollusks, the skeletons of single-celled organisms (foraminifera and coccolithophores), and ice cores to name a few (**Figure 20.11**). Ice cores contain a wealth of climate data in addition to temperature data from oxygen isotopes; they also include air bubbles that record the levels of greenhouse gases, concentrations of windblown aerosols, and ash from volcanic eruptions.

Other proxies include the extent of glacial sediment, sea level curves, pollen (palynology), and fossils. For instance, climatologists have used several features within fossil plants to reconstruct climate, largely because these organisms are sensitive to climate. These proxies include the thickness of tree rings, the shape of the leaves, and the density of pores on leaf surfaces.

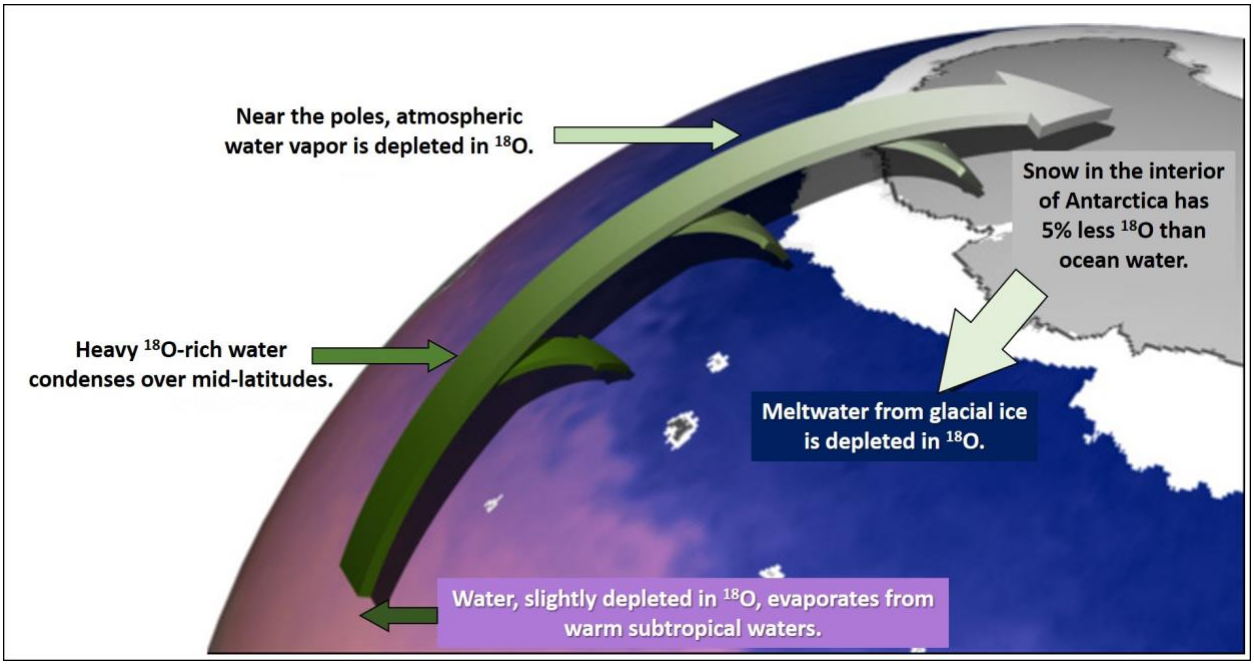


Figure 20.11: Water vapor gradually loses ^{18}O as it travels from the equator to the poles. Because water molecules with heavy ^{18}O isotopes in them condense more easily than normal water molecules, air becomes progressively depleted in ^{18}O as it travels to high latitudes and becomes colder and drier. In turn, the snow that forms most glacial ice is also depleted in ^{18}O. As glacial ice melts, it returns ^{16}O-rich fresh water to the ocean. Therefore, oxygen isotopes preserved in ocean sediments provide evidence for past ice ages and records of salinity.

By combining hundreds to thousands of individual climate records, climate scientists begin to gain insight into overall climate trends. The **Intergovernmental Panel on Climate Change (IPCC)** and the **National Oceanic and Atmospheric Administration** (NOAA) regularly compile multiple types of proxy records from across the world to reconstruct climate patterns. The accuracy of climate records very much depends on the time frame being considered, with more certainty in the patterns of the recent past (Cenozoic) and less the further back in geologic time (**Figure 20.12**).

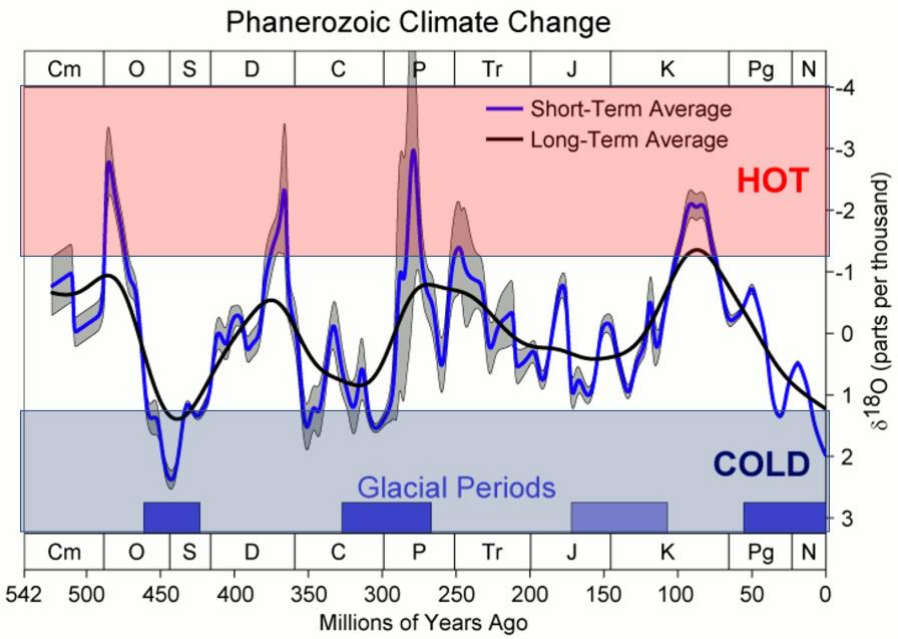


Figure 20.12: This figure shows the long-term evolution of oxygen isotope ratios during the Phanerozoic eon as measured in fossils.

There is no scientific debate surrounding the interpretation of individual proxies and the resulting climate records; however, there appear to be many-sided discussions that largely stem from the economic and political aspects of climate change. It is important to remember to consider how scientific data is presented to the public and how we make conclusions based on presented data. When presented with new data or information it is important to consider 1) the source of the data, 2) how the data was collected, 3) how the data is presented, and, most importantly, 4) what reasonable conclusions can be drawn from the data independent of opinions. Lastly, as humans who share a planet with many, we must be willing and open to a change in perspective, particularly when faced with new data and information.

Attributions

- Figure 20.10: “The Causes of Climate Change” (Public Domain; NASA)
- Figure 20.11: Derivative of “Oxygen Isotopes at the Equator and Poles” (Public Domain; Robert Simmon/NASA/GSFC via Earth Observatory) by Chloe Branciforte
- Figure 20.12: Derivative of “Phanerozoic Climate Change” (CC-BY-SA 3.0; Global Warming Art via Wikipedia) by Chloe Branciforte

Additional Resources on Climate Change

To learn more about the science behind climate change and the scientific community's position on anthropogenic climate change see the following:

- National Aeronautics and Space Administration (NASA) climate Site
- National Oceanic and Atmospheric Administration Climate Site
- Geological Society of America's Position Statement on Climate Change
- American Meteorological Society's Position Statement on Climate Change
- American Chemical Society's Position Statement on Climate Change
- American Physical Society's Position Statement on Climate Change
- American Association for the Advancement of Science's Position Statement on Climate Change

Activity 20A: Concept Sketches and Climate Change

A **concept sketch** is a simplified drawing illustrating the main aspects of landscape or system. It is annotated with concise but complete labels that identify important features. Short sentences describe the processes that are occurring. The final aim is to show the relationships between features and processes. It is not simply a sketch labeled with only the names of features. See a rubric below for what is expected for each success level. Point values will be determined by your instructor.

Skill	Emerging	Progressing	Partial Mastery	Mastery
Identify **Features**	Incomplete labeling.	Some labeling.	Most clearly labeled.	Relevant features clearly labeled.
Identify **Processes**	Incomplete identification and description.	Incomplete identification or description.	Clear identification and description.	Relevant processes clearly identified and described.
Explain **the Connections and Relationships Between Features/Processes**	Incomplete connections/relationships.	Suggests some connections/relationship.	Most connections/relationships highlighted effectively.	Relevant connections/relationships highlighted effectively.
Demonstrate **Proper Use of Terminology**	Incomplete or inappropriate use of terminology/units. Frequent errors and misunderstanding of the subject.	Attempts use of appropriate terminology/units. Some errors and missing components.	Consistent use of appropriate terminology/units. Few errors or missing components.	Consistent and successful use of appropriate terminology/units.
Assess **Scientific Accuracy**	Lacks organization with frequent errors, demonstrating misunderstanding of the subject.	Drawings are readable, with occasional oversimplifications, errors and/or missing components.	Drawings are readable. Consistent use of symbology and/or colors/patterns to illustrate major features and/or processes.	Drawings are clearly readable with accurate details illustrated through appropriate symbols and/or colors/patterns. Sketch shows a scale.

Table 5.3: Rubric for geology concept sketches.

More on Concept Maps is available via NAGT/SERC, Teach the Earth.

1. Draw a concept sketch of a **positive feedback loop**. Labels should be short sentences explaining the relationships between geologic features and processes.

2. Draw a concept sketch of a **negative feedback loop**. Labels should be short sentences explaining the relationships between geologic features and processes.

Attributions

- Table 5.3: “Concept Sketch Rubric” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 20B: Drought and Wildfires in California

Rising global average temperature is associated with widespread changes in weather patterns. Scientific studies indicate that extreme weather events, such as heat waves and large storms, are likely to become more frequent or more intense with human-induced climate change.

The last decade was the hottest on record with many extreme temperature conditions becoming more common, particularly in the western US. In addition to hot temperatures, the Southwest, in particular, has experienced less precipitation than usual; this already arid region is sensitive to changes in temperature and thus vulnerable to drought, and even a small decrease in water availability can stress natural systems and further threaten water supplies.

1. Visit **Drought.gov** and enter your zip code to determine your region's current drought level. Report what you find below.
    a. Drought status:
    b. Precipitation total:
    c. Average high temperature in the last 7 days:

2. Answer the following questions using **Drought.gov**:
    a. What is the current percentage of the US land area experiencing drought?:
    b. Currently, how many people are experiencing drought?:

3. Next visit **California's drought map**.
    a. How many residents are currently in drought?
    b. What percentage is this of the state population?
    c. How many more Californians reside currently in abnormally dry areas?
    d. What percentage is this of the state population?
    e. On the map portion locate your county.
        i. County name:
        ii. Indicate the drought level for your county here:

Climate change is increasing the frequency and severity of wildfires not only in California but all over the world. Since 1950, the area burned by California wildfires each year has been

increasing, as spring and summer temperatures have warmed and spring snowmelt has occurred earlier. During 2020 (as of November), California experienced five of the six largest fires ever recorded, in almost a century of records.

Unfortunately, many of us here in California have experienced the impacts of wildfires firsthand. For this next section, some may feel anxious or upset answering questions regarding what are perhaps local fire events. Talk with your instructor for guidance; you may choose to skip ahead to the "Sea Level Rise and Climate Change" section.

4. Visit the **Cal Fire page**. Bookmark this page as it will be a valuable tool for future fire events. Scroll down and from the Incident Archive, determine the following for the most recent fire to affect your area:
    a. Estimate acres burned:
    b. Number of incidents:
    c. Structures damaged or destroyed:

Activity 20C: Sea Level Rise and Climate Change

Navigate to **NASA Sea Level Change**.

1. What is the latest measurement for sea level? *Remember to include units!*

2. Examine the graph showing satellite data from 1993-present.
    a. What can you interpret from this graph?
    b. What is the current rate of sea level change? *Remember to include units!*

Global mean sea level has risen about 8 inches (20 cm) since 1880; three of those eight inches occurred in the last 25 years. The rising water level is due to a combination of meltwater from glaciers and ice sheets and thermal expansion of seawater as it warms. In 2019, global mean sea level was 3.4 inches (86.4 mm) above the 1993 average, earning the distinction as the highest annual average in the satellite record (1993-present) (**Figure 20.13**).

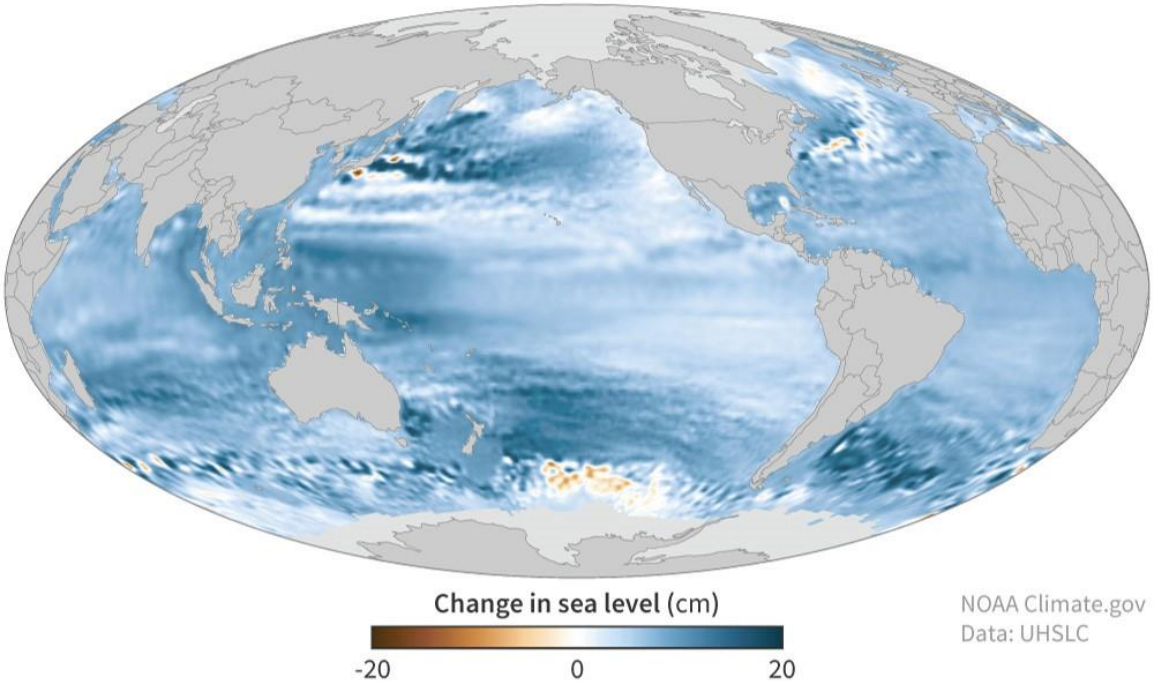


Figure 20.13: Sea Level Change between 1993 and 2019, mean sea level has risen across most of the world ocean (blue colors). In some ocean basins, sea level has risen 6-8 inches (15-20 centimeters). Rates of local sea level (dots) can be amplified by geological processes like ground settling or offset by processes like the centuries-long rebound of land masses from the loss of ice age glaciers.

Navigate to the **NOAA - Sea Level Rise Viewer**. Your instructor will provide a coastal community for you to zoom into on the map. Click the "Sea Level Rise" icon along the left-hand toolbar. With this tool you can select how much sea level will rise.

3. Raise sea level to 1 ft. Along the top toolbar there is a "Legend Toggle" available, click this so you can see what all the symbols and colors signify. Are there significant changes in your assigned community?

4. Keep raising sea level in 1-foot intervals, until you reach the 10 ft water level. As you raise sea level take note of what areas are vulnerable or impacted by coastal flooding, low lying, etc. Summarize your findings for your community.

5. How do you think this will impact the people in your selected community?

The demands of increasing human population along our coastlines create competition with coastal habitat preservation and with recreational and commercial uses of the coast and nearshore waters. As climate changes over the coming century, the problems facing coastal communities will likely worsen. Good management and policy decisionmaking require baseline information on the rates, trends, and scientific understanding of the processes of coastal change on a regional to national scale.

It can be challenging for the public, conservationists, and policy makers to agree on how to combat rising sea level while saving structures, the environment, and their communities. Planning and mitigation are never easy. There are many questions that must be considered; for example: What decisions are required? How are they agreed upon? Who should be involved? How much will it cost? Will the natural environment be impacted? All are important questions, and only represent a fraction of those asked in real scenarios.

6. Visit **The Ocean Game from the LA Times** and strategize to successfully save your hypothetical community. Once you have completed the game, summarize what you learned below.

7. Read this article from the LA Times for additional information about rising sea level and California. Summarize your thoughts on this topic below.

Attributions

- Figure 20.13: “Phanerozoic Climate Change” (Public Domain; Philip Thompson, University of Hawaii/NOAA via Climate.gov)

Activity 20D: Ice Cores and Climate Change

1. Watch this video from the National Science Foundation (NSF) on how **scientists recover and study ice cores** and then answer the following question: What does each layer of an ice core represent?

2. From the video you'll notice that scientists meticulously mark and label the **ice cores** (this is also true for sediment and rock cores). Why do they mark and label the cores? After a core is drilled, it is removed from its environment and stored in a freezer facility, like the National Science Foundation Ice Core Facility (NSF-ICF), for further research and study. With no labels, the context of the core is lost which is detrimental to research. To prevent this, scientists ensure the core is labeled, usually in multiple ways and on all sides. To ensure this doesn't happen to your own core, you will need to indicate the following items on your **Life Core**:
    a. Draw an arrow indicating "**UP**" (assume this points to the top of the page).
    b. Label the **TOP** of the core.
    c. Label the **BOTTOM** of the core.

3. Select emojis from **Emojipedia** to represent major, shareable events from your life. Layer your emojis in your **Life Core**, beginning with the oldest event at the bottom and the most recent event at the top.

4. Once completed, share or trade your Life Core with a classmate (or follow your instructors directions). Be sure to complete this step without discussing the cores with anyone.

5. On the Core Logging Sheet record observations regarding your classmate's Life Core. Note any patterns, similarities, recognizable objects or events, etc. After recording your observations, use them to support conclusions regarding your classmate's life. Once completed, summarize your findings on the Life Core Summary page.

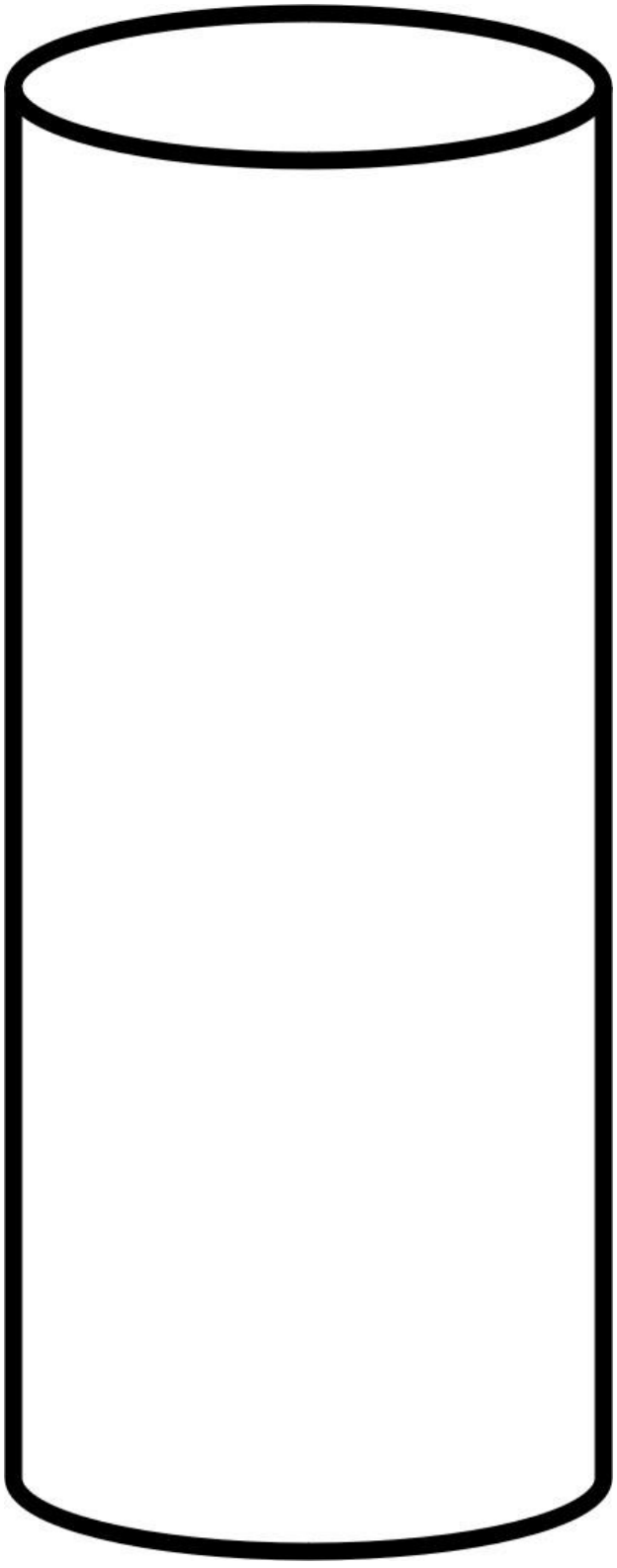


Figure 20.14: Questions 3-6 in Activity 20D.

Core Logging Sheet

Observations	Conclusions

Life Core Summary

***Summarize your findings on this page**, remember your observations should be used to support the conclusions you draw regarding your classmates' Life Core.*

***Follow up question:** What additional information would help ensure your conclusions were accurate? Why?*

Attributions

- Figure 20.14: “Ice Core” (CC-BY 4.0; Chloe Branciforte, own work)

Activity 20E: Sea Ice and Climate Change

Scientists at the **National Snow and Ice Data Center (NSIDC)** have measured the extent of Arctic and Antarctic sea ice every month since at least 1978 using satellite data. A data table (**Table 20.1**) from NSIDC for September in the Arctic and February in the Antarctic is provided below. For the following questions, use **Table 20.1** and the **interactive sea ice viewer from NSIDC**.

Arctic Sea Ice

1. What was the average extent of Arctic sea ice in September from 2005 to 2020 in millions of km^2? Give your answer to the nearest hundredth.

2. Plot all of the data for the extent of Arctic sea ice from 2005 to 2020 on the graph labeled "**Arctic**". Then, draw a straight line (a **best-fit line**) through the points so that the number of points above the line is about the same as the number below the line.

3. Based on your plot and calculations in the previous two questions, would you say the amount of Arctic sea ice as measured in September of each year is decreasing, increasing, or staying about the same?

4. What do you predict the extent of Arctic sea ice will be in 2030?

Antarctic Sea Ice

5. What was the average extent of Antarctic sea ice in September from 2005 to 2020 in millions of km^2? Give your answer to the nearest hundredth.

6. Plot all of the data for the extent of Antarctic sea ice from 2005 to 2020 on the graph labeled "**Antarctic**". Then, draw a **best-fit line** through the points.

7. What do you predict the extent of Antarctic sea ice will be in 2030?

8. Based on your responses to the last few questions, would you say that the annual amount of Antarctic sea ice as measured in February of each year is decreasing, increasing, or staying about the same?

9. How do the changes in Arctic sea ice extent over time compare with the Antarctic changes? If they are different, why do you think that might be?

Summer Extent of Sea Ice 2005-2020		
Year	**September in Arctic, in millions of square km**	**February in Antarctic, in million of square km**
2020	3.92	2.71
2019	4.19	2.46
2018	4.66	2.28
2017	4.67	2.15
2016	4.17	2.74
2015	4.43	3.65
2014	5.29	3.90
2013	5.05	3.80
2012	3.39	3.24
2011	4.34	2.34
2010	4.62	3.11
2009	5.12	2.90
2008	4.59	3.95
2007	4.16	2.92
2006	5.7	2.60
2005	5.32	2.96

Table 20.1: Use this table for Activity 20E: Sea Ice and Climate Change.

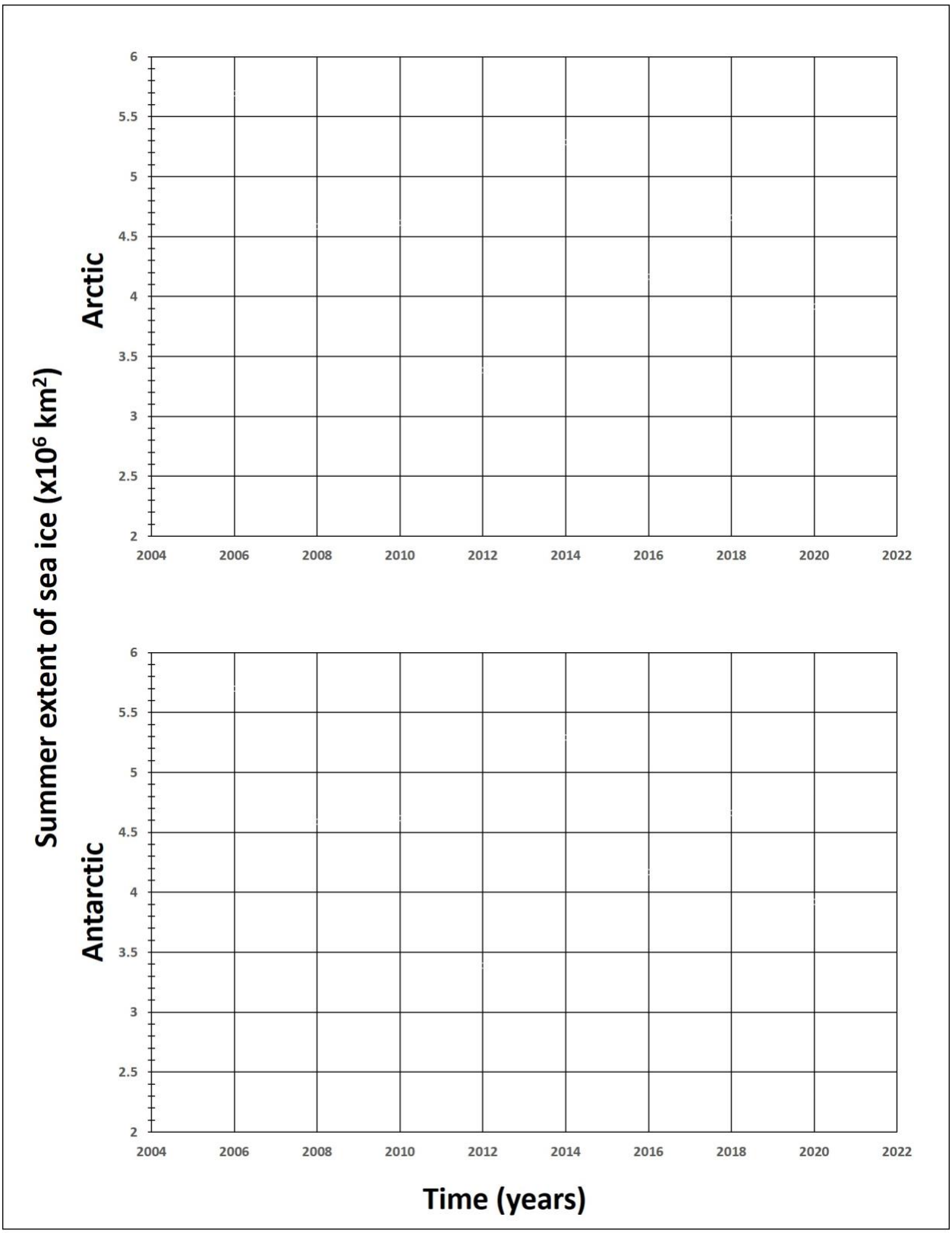


Chart 20.1: Use this graph for Activity 20E: Sea Ice and Climate Change.

Drawing conclusions about any complex system, such as climate and how it is changing, is difficult. Completely accurate data can be misrepresented and taken out of context (e.g. examining sea ice extent without understanding ocean currents), which may lead someone to an incorrect conclusion. It is important to base any conclusion on rational, accurate, complete, and in-context data, rather than data that has been poorly collected or misrepresented. Most importantly, you should come to your own well-informed conclusions regarding data, rather than be swayed by the opinion of the author presenting the data; this is true both in science and in many other aspects of your life.

10. Do you think any conclusions regarding climate change should be made based on the data presented in this assignment/lab?

11. What data do you think are needed to make a conclusion regarding climate change?

Attributions

- Table 20.1: “Summer Extent of Sea Ice 2005-2020” (CC-BY 4.0; Chloe Branciforte, own work, data via NSIDC)
- Chart 20.1: “Summer Extent of Sea Ice” (CC-BY 4.0; Chloe Branciforte, own work)