

Investigating the Earth: Exercises for Physical Geology

INVESTIGATING THE EARTH: EXERCISES FOR PHYSICAL GEOLOGY

DANIEL HAUPTVOGEL; VIRGINIA SISSON; AND MICHAEL COMAS



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PREFACE

About the Authors

Drs. Daniel Hauptvogel and Virginia Sisson are instructional faculty in the [Department of Earth and Atmospheric Sciences at the University of Houston](#). We are a team that shares many responsibilities, including the oversight and training of our department's ~64 graduate teaching assistants, directors of our Geoscience Learning Center where our teaching assistants hold their office hours and students come in for tutoring, coordinators for about 15 sections of physical geology lab per semester, and a few sections of historical geology lab per year. Michael Comas was a graduate student at UH who made significant contributions.

Daniel Hauptvogel



Dr. Daniel Hauptvogel

I'm an Instructional Associate Professor and have been at UH since 2015. Currently, I teach GEOL 1303 Physical Geology and GEOL 1370 Natural Disasters. I received a Teaching Excellence Award in 2019 and the John C. Butler Excellence in Teaching Award in 2023. I was born and raised in New Jersey, where I attended Montclair State University for my B.S. and M.S. in geology and went to The Graduate School and University Center of the City University of New York for my Ph.D. I didn't start as a geology major though, in fact, I didn't declare geology as my major until my junior year. I sort of floundered around trying to figure out what I wanted to do, and my grades showed it. However, once I joined the geology program, I felt at home, and it has been smooth sailing ever since.

My graduate training in geology was in paleoclimate with a focus on sediment geochemistry, particularly in Antarctica. I began research on Antarctica as an undergraduate after my mineralogy professor suggested I get involved in undergraduate research. I continued to study Antarctica with different projects throughout my Master's and Ph.D. Today, I find myself more interested in geoscience education and student success.

I credit my initial interest in geology to my grandfather, who lived in the Rocky Mountains of northwestern Montana near Glacier National Park. During my visits, we went to various mountains, lakes, parks, etc. The most memorable of which was [Hidden Lake](#) in Glacier National Park. I was too young to appreciate the views and the geologic significance of the area, but now I'm longing to return there.

Virginia Sisson



Dr. Virginia Sisson

I'm an Instructional Professor and the co-director of the UH summer field geology camp at the Yellowstone Bighorn Research Association camp near Red Lodge, Montana. For this, I got the ExxonMobil-Geological Society of America Field Camp Excellence Award. Before I moved to Houston, I did my Ph.D. at Princeton University and an A.B. at Bryn Mawr College. Initially, I worked at Rice University before moving across town to UH. Now, I teach Physical Geology and create virtual field trips. In 2023, I received the Grover Murray Outstanding Educator award from the American Association of Petroleum Geologists. I also am a fellow of the Geological Society of America and Mineralogical Society of America.

Like many geologists, I went to college planning on another major. In high school, I loved hiking and backpacking and walked the Long Trail through Vermont and the Appalachian Trail through Maine. These experiences cemented my love of being outdoors. Also, one of my uncles was a geologist and my piano teacher used to bring me fossils from her hometown. So, I decided to try geology. Then I saw all the places that my geology professors had traveled, I quickly switched my major to geology. Prior to coming to UH, I did field work in British Columbia, Alaska, and Venezuela working on metamorphic rocks (and sometimes igneous rocks as well). Now when I'm back in Houston, I use tools such as geochemistry, geochronology, fluid inclusions, cathodoluminescence, remote sensing, UAVs (drones), structural geology, and tectonics. Some of my research has touched on global geochemical cycles. Recently, I've focused on the geology of jade and associated rock in Guatemala.

Michael Comas



Michael Comas

I graduated with a Master's in Geology from UH in 2023 and am now a geologist at an environmental consulting firm in Atlanta, Georgia. I grew up in Birmingham, Alabama and completed my undergraduate degree in Environmental Science from the University of Alabama in 2020. My love and desire to learn more about the outdoors started from a young age. I began hiking with my father just about as soon as I could walk and eventually joined the Boy Scouts which is where my interest in our environment truly blossomed. When I initially began my undergraduate degree at UA I was studying finance, but I found myself largely disinterested in the coursework. The call of the outdoors beckoned me, and I decided to switch my major to Environmental Science late in my sophomore year. I believe this decision was perhaps the most important one of my life thus far.

I soon began to get involved in different labs studying and working under many talented scientists. I conducted work on forestry dynamics, volcanic lightning, and micro paleontology. This ultimately led me to develop a passion for climate science and sedimentology and my connections through UA lab work afforded me the chance to join a lab at the University of Houston studying modern glacial dynamics in Antarctica for my Master's. Being from Alabama, snow and ice had always fascinated me as I was only able to see it once every year or so when the conditions were just right. You can imagine how dumbfounded I was upon seeing icebergs larger than US states and an ice sheet that covered an entire continent when I traveled to Antarctica for field work in early 2022.

Not only was I able to conduct field work in Antarctica, but I also studied sediments in the field across the Western US in Washington, Utah, and Wyoming. Closer to home, I worked with atmospheric scientists at UH to study ozone interaction over Galveston Bay to better understand the complicated relationships between the area's subtropical climate, summer storms, industrial emissions, high ozone levels, public

health, and socioeconomics. On top of field work, I taught undergraduate laboratory courses in Physical Geology, Sedimentology/Stratigraphy, and Field Methods during my time at UH. My teaching allowed me to further develop my passion for graphic design which I discovered through my thesis work. I feel incredibly lucky to have been able to see and learn so much about our world through my studies, and I have no desire to slow down any time soon.

Other Contributors

Many people contributed to the creation of this lab manual in the form of exercises, images, and editing, including several graduate students from the University of Houston.

- Lizabeth Arellano – UH Ph.D. student
- Tom Lapen – UH professor
- Dave Layzell – University of Calgary professor
- Alex Maze – Michigan Tech undergrad student
- Andrea Paris – UH Ph.D. student
- Alex Robinson – UH professor
- Will Sager – UH professor
- Somaria Sammy – UH M.S. student
- Kaitlin Thomas – UH M.S. student
- Ana Vielma – UH Ph.D. student
- Yin-Kai Wang – UH Ph.D. student
- Jonny Wu – UH Professor now at University of Arizona
- Xiao Yu – UH Ph.D. student

About this Lab Manual

While there are plenty of options available for Physical Geology lab manuals, we wanted to create a low-cost option for our students. Hence, this lab manual that speaks to the nature of our teaching philosophy, giving our students a quality education and encouraging them to observe and think about the world around them. There are many physical processes that have formed our Earth. We hope you enjoy exploring these. If you continue on in geology and take Historical Geology, you may want to use our open access lab book, *The Story of Earth: An Observational Guide*, 2nd Ed.

Through our own teaching experiences, we have found that students have difficulty making observations and interpreting them. Perhaps this results from the abundance of standardized tests students must take throughout their school career, but nonetheless, it is a problem that we have observed. Our philosophy is that learning is best done by doing and thinking. Perhaps this Japanese proverb, “Better than a thousand days of diligent study is one day with a great teacher” can be changed to include a day with a great lab manual.

Our goal in creating the material for this lab manual was to focus making observations of geologic data as we want you to look at things and wonder why and how they formed. The exercises and examples used in this book are scattered throughout the world. We wanted to make sure that one region of the world was not the sole focus of this work.

As you read the chapters, you'll notice the tone of the text is very casual. This was important to us because many geology texts are dense and, at times, complicated to read because of the vocabulary. Complicated text is more than likely not going to be read by students. Therefore, we have tried to break down concepts and terms into simple explanations and discussions.

We were fortunate enough to have our University Library sponsor our participation in the [Rebus Text-](#)

[book Success Program](#), a year-long program on creating open-access materials. The experience is a must for anyone wanting to create quality open-access materials. They also provided a grant to support our efforts.

If you are a faculty member or teaching assistant using this lab book for the first time, please contact us for our guide to teaching and possible answers. Many of the answers are open-ended, with several possible interpretations of the same data. This is part of our philosophy that data is open to interpretation, and there might not be one correct answer. For students reading this, just try your best and discuss why you believe your interpretation may be right with your professor or TA.

Citing This Book

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Accessibility

We have designed this lab manual with accessibility in mind using [W3C standards](#). All text has proper headings, text, and background coloring meet the highest standards with a contrast ratio of at least 7:1, all images have descriptive alt text, and all hyperlinks open in the same window (you'll need to right-click links to open them in a new tab or window). If you find any accessibility errors or have suggestions to improve accessibility, please contact Daniel Hauptvogel at dwhauptvogel@uh.edu.

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CHAPTER 1: INTRODUCTION TO SCIENCE AND GEOLOGY

Scientific Method, Maps, and Density

Learning Objectives

The goals of this chapter are to:

- Get to know your classmates
- Use the scientific method as practiced by geologists
- Review accuracy, precision, and extrapolation of data
- Recognize map fundamentals
- Understand density

1.1 The Language of Science

Science is the study of natural phenomena. The language used in science can be confusing sometimes. Many often use terms like **fact**, **hypothesis**, **law**, and **theory** to explain natural phenomena incorrectly. The distinction between these terms is subtle. Theories, laws, and facts can start as hypotheses when they are first proposed and before they are rigorously tested. Generally, a fact is a very elementary statement based on some measurement, such as water boiling at 100 °C (212 °F). A Law is based on a collection of individual facts and is an attempt (usually with mathematics) to relate one set of measurable quantities to another (mass, speed, temperature, viscosity). Example, $F=ma$, $V = d/t$, $PV = nkT$. A theory attempts to explain why certain laws exist and why certain facts are true under specific conditions. Example 1: Planetary orbits are elliptical (fact) because gravity is an inverse-square force (law), and matter operates under Newton's Laws of Motion. Example 2: Matter is comprised of atoms, and this explains how gases behave (laws), why we have specific chemical reactions (laws), and why the Periodic Table exists (facts). Are some facts more certain than others? Water always boils at 212° F at sea level, but at higher altitudes, it boils at lower temperatures. So, every fact depends on the specific circumstances under which it was measured.

- **Fact** – A basic statement based on some measurement, experiment, or observation. All facts are true under specific conditions.
- **Hypothesis** – A tentative statement such as 'if A happens, then B must happen' that can be tested by direct experiment or observation. A proven hypothesis can be expressed as a law or a theory.
- **Law** – A logical relationship between two or more things based on facts and proven hypotheses. It is often a mathematical statement of how two or more quantities relate.
- **Theory** – An explanation for why certain laws and facts exist that can be tested to determine their accuracy.
- **Belief** – A statement that is not scientifically provable in the same way as facts, laws, hypotheses, or theories.

Exercise 1.1 – The Vocabulary of Science

Sort the statements below as an example of a fact, hypothesis, law, theory, or belief.

The diameter of the Earth is 12,756 km (7,926 mi).	Albert Einstein explained that massive objects (like the Earth) cause a distortion in space-time, which is experienced as gravity.
Aliens exist.	Energy and mass can neither be created nor destroyed.
Water freezes at 32°F (0°C).	For every action, there is an equal and opposite reaction.
The position of the planets can cause humans to act in specific ways.	The bell will ring at the end of the period.
The universe started with a massive expansion of space and time called the Big Bang.	Species evolve.
The oldest layers of rock are deeper, while the youngest layers are towards the top.	Some numbers are luckier than others.
Students who eat breakfast will perform better on a math exam than those who do not.	Species evolve through a process known as natural selection, in which certain organisms survive and reproduce more than others.
There are such things as ghosts.	Drinking sugary drinks daily leads to being overweight.
Humans are made of cells.	Force = mass x acceleration ($F=ma$)
Students who bring their own lunch spend less money throughout the day.	A meteorite impact caused the dinosaur extinction.

1.2 The Scientific Method

The scientific method is a step-by-step procedure for how many scientists study the world. Often, scientists begin by observing some event or object and want to know why the event happened or why the object formed. Then, they develop a hypothesis to explain their observation and create an experiment to test the hypothesis. If the test results support the hypothesis, they develop a conclusion about the event or object. If the results don't support the hypothesis, they go back, alter it accordingly, and retest it.

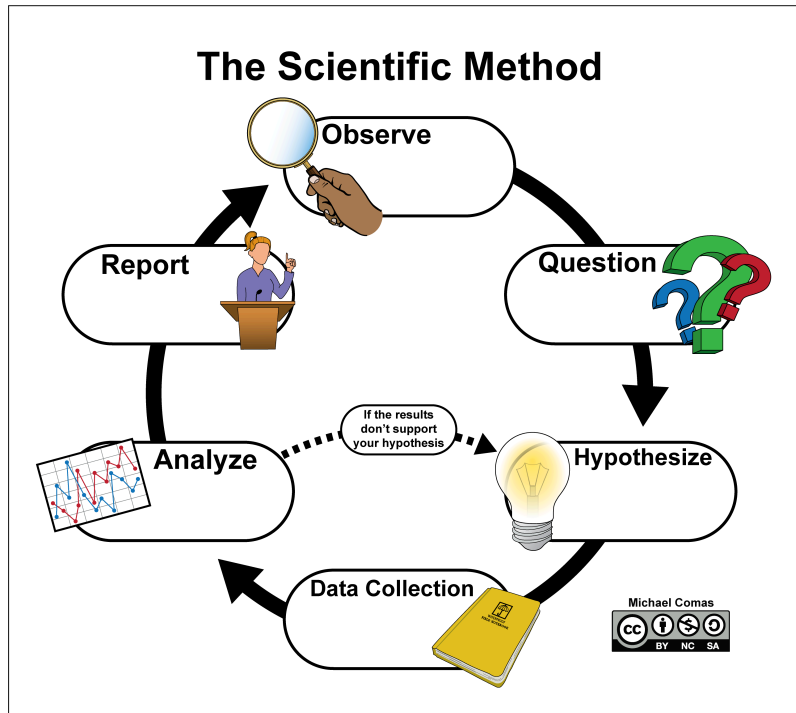


Figure 1.1 – Flow chart for the scientific method. Often a geoscientist starts with observations and then moves to the next step ending in reporting on their results. Image credit: Michael Comas, CC BY-NC-SA.

Exercise 1.2 – Everyday Use for the Scientific Method

You walk into an empty classroom and attempt to turn on the projector, but it doesn't turn on (Figure 1.2). Use the scientific method to investigate and solve your problem. Write a statement about your issue for each step of the scientific method.



Figure 1.2 – An empty classroom where the projector is not working. Image credit: [Pexels](#), Public Domain.

a. What is your observation?

b. What is your question?

c. What is your hypothesis?

d. What is your data?

e. What is your analysis?

f. What is your conclusion?

The Scientific Method and Geology

The scientific method in geology can look quite different. This is because many of the events that geologists investigate have already happened; so, they can't make any direct observations. What geologists find is the evidence left behind by that event. An example is a solidified lava flow. Geologists know the lava likely came from a volcano, but they didn't observe the eruption and can't test the hypothesis by creating a new eruption. They have to rely on facts they know about current lava flows and volcanic eruptions to interpret past ones. In a sense, you might consider geology to be a historical science. Geology is the intersection of the other sciences (chemistry, physics, biology, and mathematics) applied to studying the Earth.

Uncertainty

Because geologists often study past events they can't directly observe, they must deal with uncertainty. Uncertainty in science doesn't mean that scientists don't believe their results or that their research is flawed. It represents natural variability in taking measurements. Often a scientific investigation does not yield an exact measurement. Instead, scientists make repeated experiments that give a range of measurements around a central value. This is where **accuracy**, **precision**, and statistics come in (Figure 1.3). For every measurement we make, there is an actual value that we are trying to obtain. In the next exercise, you will determine the weight of a rock. Simply put, accuracy is how close a measurement is to the actual true value, whereas precision is how close those measurements tend to be to each other.

For example, if geologists are trying to figure out when a volcano erupted lava, they would radiometrically date the solidified lava flow to determine when it formed (a topic discussed later). Remember, a single measurement may not be accurate; thus, repeated measurements are needed. If the measurements are around the same age, geologists are more certain about their results.

When doing any calculations for this or other exercises, you should consider the number of significant digits that you use. Your calculator will give you many **significant digits**, but these may not be appropriate for your result. The number of significant digits for your answers depends on the way you calculate. For addition and subtraction, round to the lowest significant number. For multiplication and division, your final answer should have the same number of significant digits as the least precise value given in the original problem. If you have forgotten how to do this, here is a [refresher](#).

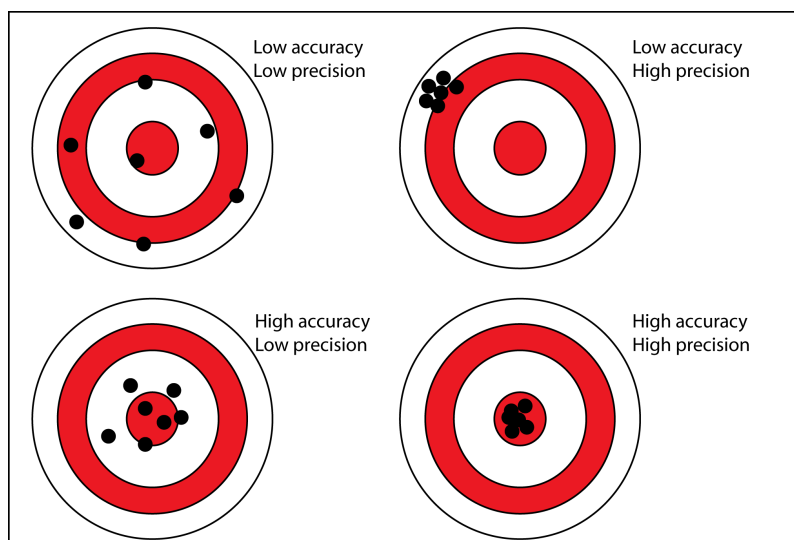


Figure 1.3 – Shots at a target demonstrate precision versus accuracy. Accurate measurements fall in the bull's eye. Precise measurements are tightly clustered. Accurate and precise measurements are tightly clustered in the bull's eye. Image credit: [Bethan Davies](#), CC BY-NC-SA.

Exercise 1.3 – Working with Uncertainty

Your instructor has given your group a rock sample of unknown weight and an object of known weight.

- Each student should feel how heavy the object of known weight is. Then, each should heft the unknown rock sample in their hand and determine how much they think the rock weighs. Record these measurements in Table 1.1.

Table 1.1 – Rock measurements by hand

Student	Weight of unknown rock (g)
1	
2	
3	
4	
5	
6	

- What was the total range of measurements? _____
- What is the average of your measurements done by hand (use the appropriate significant digits)?

- Do you think your measurements are precise, accurate, both, or neither? Explain.

- e. Now, measure the weight of the rock sample on several scales provided by your instructor and report the results in Table 1.2.

Table 1.2 – Rock measurements by scale

Scale	Weight of unknown rock (g)
1	
2	
3	
4	
5	
6	

- f. What was the total range of measurements? _____
- g. What is the average of your measurements done using a scale (use the appropriate significant digits)?

- h. Do you think your measurements are precise, accurate, both, or neither? Explain.

- i. How close were your measurements done by hand to your scale measurements?

- j. **Critical Thinking:** What do you think is responsible for the differences in your measurements on the scales?

Extrapolation

Geologists often have limited data to work with to form hypotheses and analyses; after collecting data, they extrapolate their results. Extrapolation is a type of estimation based on current data. Imagine you are a geologist working in a tropical rainforest. Do you think you will find many rocks? Probably not, and if you do find any they are probably in rivers. Here's the cool part, whatever you figure out about these rocks, you can guess that the whole rainforest has the same rocks. That's extrapolation!

Exercise 1.4 – Extrapolation

Most of the world's population has dark hair. In the United States, 85 percent of the population has black hair, while 11 percent has brown hair. Authentic blonde hair, which is quite rare, accounts for only 2 percent of the American population. Genuine red hair, the rarest of all hair colors, accounts for just 1 percent of the American population. How did scientists come up with this? To test this, let's look at hair color on various scales.

- a. Identify the hair color of the students in your group. Determine the number of students with each hair color and what percentage they make up. To calculate percent: (number of students with black hair / total number of students) x 100.

Table 1.3 – Hair color of students in your group

Hair Color	Number of students	Percentage of students
Black		
Blonde		
Brown		
Red		
White/Gray		
Other:		

- b. Develop a statement about the most common and least common hair color in your group.

- c. With your limited data, is it reasonable to extrapolate the percentages of hair colors in your group for the entire class? Explain.

- d. Now complete the same chart again about your entire class.

Table 1.4 – Hair color of students in your class

Hair Color	Number of students	Percentage of students
Black		
Blonde		
Brown		
Red		
White/Gray		
Other:		

- e. Did your original statement apply to the entire class? Explain.

- f. Think about one of your lecture classes. Are the percentages of the different hair colors the same as for this lab?

- g. Can your group and class data be extrapolated to the entire US?

1.3 The Scale of Geology

Geologists work at various scales, from continents and mountain ranges to the atoms that make up rocks and minerals. Some scales like geologic time, are so big they're difficult to truly comprehend. The Earth is 4,540,000,000 years old. To put this into perspective, if you have a penny for every year the Earth has been around, you will have \$45.4 million! More on geologic time in another chapter.

Exercise 1.5 – Distance and Scale

Geologists do a lot of measuring, whether it's distance, age, rates, etc. They also need to convert units, especially in the United States, where the metric system is not the norm.

- a. The accepted age of the Earth is 4.54 billion years old. If the average human lifetime is 72 years, how

- many human lifetimes has the Earth been around for? _____
- The generally accepted distance to reach outer space from the surface of the Earth is 100 km, called the Kármán Line. What is that distance in miles? (1 km = 0.62 mi) _____
 - The distance to the center of the Earth is 6,371 km. What is that distance in miles? _____
 - If you could drive to the center of the Earth at a highway speed of 65 mph, how many hours would it take for you to get there? _____
 - Open [Google Earth](#) and measure the distance from New York City, NY, to San Francisco, CA, in kilometers and miles. What are the distances? _____
 - Find a similar distance on another continent between two cities. Which two cities are they?

1.4 Maps, Maps, Maps

Maps are to a geologist as a wrench is to a mechanic, a common tool used to perform job duties. Geologists have their own type of map, aptly called a geologic map... very original. We'll look at geologic maps later, but right now, you need a refresher on how to read basic map information.

Latitude and Longitude

Latitude and longitude constitute a geographic coordinate system used to locate positions on the Earth's surface. Lines of latitude run from east to west, and lines of longitude run from north to south (Figure 1.4). The reference point for latitude is the equator (0°), which separates the northern and southern hemispheres. Degrees latitude go from 0° to 90°; positive values indicate a location north of the equator and negative values indicate a location south of the equator. The reference point for longitude is the Prime Meridian (0°), which separates the eastern and western hemispheres. Some maps show longitude from 0° to 359°, while others go from 0° to 180° for east of the prime meridian and 0° to -180° for locations west of the prime meridian.

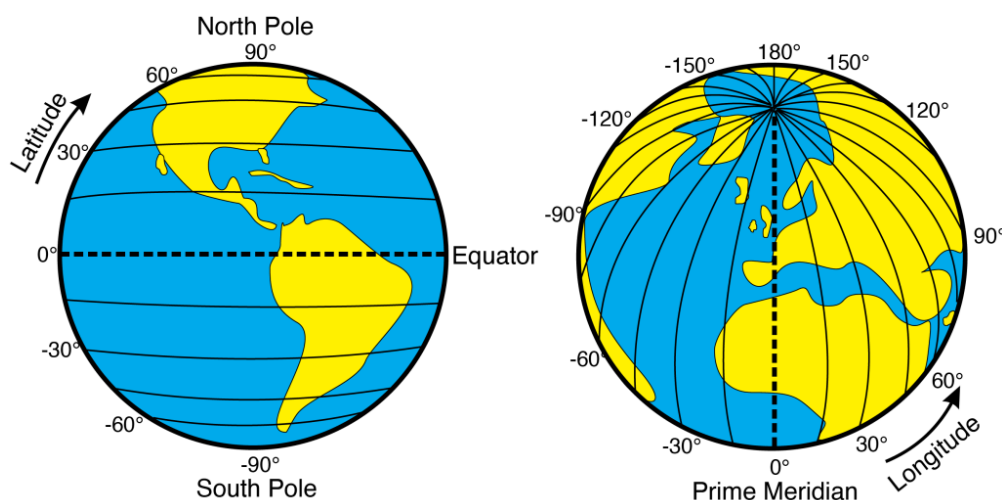


Figure 1.4 – Lines of latitude on longitude on a globe. Image Credit: Modified from Wikimedia user Djexplo, CC 0, Public Domain.

Combining latitude and longitude provides a unique coordinate to every bit of space on Earth's surface. For example, Mt. Fuji in Japan is located at about 35°N 138°E. A more precise location for Mt. Fuji is 35°21'38"N 138°43'39"E. This coordinate system is in degrees (°), minutes ('), and seconds ("), also known as DMS. Degrees range from 0 to 90, while minutes and seconds range from 0 to 60. Another way to display these spherical coordinates is using decimal degrees (DD). Those same coordinates for Mt. Fuji using decimal degrees are 35.36056°N 138.72750°E. While DMS is the classic way of representing coordinates, decimal degrees are easier when creating maps and plotting data with software.

One degree of latitude is approximately 111 km (364,000 ft or 69 mi), one minute equals 1.85 km (6,068 ft or 1.15 mi), and one second equals 30.8 m (101 ft). This is constant for all distances between points of latitude. Because longitude lines meet at the poles, lines are equidistant at the equator and get closer as you move toward one of the poles. At the equator, lines of longitude are 111 km (364,000 ft or 69 miles) apart. By 60° latitude, the distance between longitude lines is down to 56 km (35 mi). By 90°, the distance reaches zero. This explains why 2-dimensional maps of Earth distort landmasses to the south or north.

Exercise 1.6 – Latitude and Longitude

Let's get some practice finding coordinates and measuring distances. Use Google Earth or a globe provided by your instructor to answer the following questions.

- a. Which ten countries does the equator pass through?

- b. Which eight countries does the prime meridian pass through?

- c. What are the geographic coordinates for your college/university? _____

- d. Using the latitude (to the nearest degree), how far north or south of the equator is your college/university in miles and kilometers? _____

- e. What are the coordinates for New York City, New York, and London, England? _____

- f. In kilometers and miles, how much further north of the equator is London compared to New York City?

- g. What are the coordinates for the southernmost point in the continental United States?

- h. Which is at higher latitude, the border between the state of Washington and Canada or the border between Maine and Canada? What is the approximate latitude of each?

- i. Outside of Antarctica, which continent has the closest location to the south pole, and what are the coordinates (mainland only, no islands)? _____

This exercise is adapted from [Mark W. Bowen](#), Minnesota State University, Mankato.

Topography

Throughout this book, we'll look at various types of maps, including topographic maps. A topographic map shows changes in land surface elevation using topographic lines. This is how you can tell when a landscape feature is flat, mountainous, steep, shallow, etc., when looking at a map. A proper introduction to topographic maps will come later, but Exercise 1.6 is going to let you explore some of the rules.

Exercise 1.7 – Thinking About Topographic Maps

The Geoscience Learning Center at the University of Houston is equipped with several unique pieces of equipment for hands-on experience with geologic landscapes and processes. One of these tools is an interactive augmented reality sandbox capable of visually projecting topographic data in real-time onto the sandbox surface. Here, students can shape a “landscape” with their hands and watch as the projector provides a color gradient and topographic contour lines to represent variability in elevation across the sandbox (Figure 1.5).

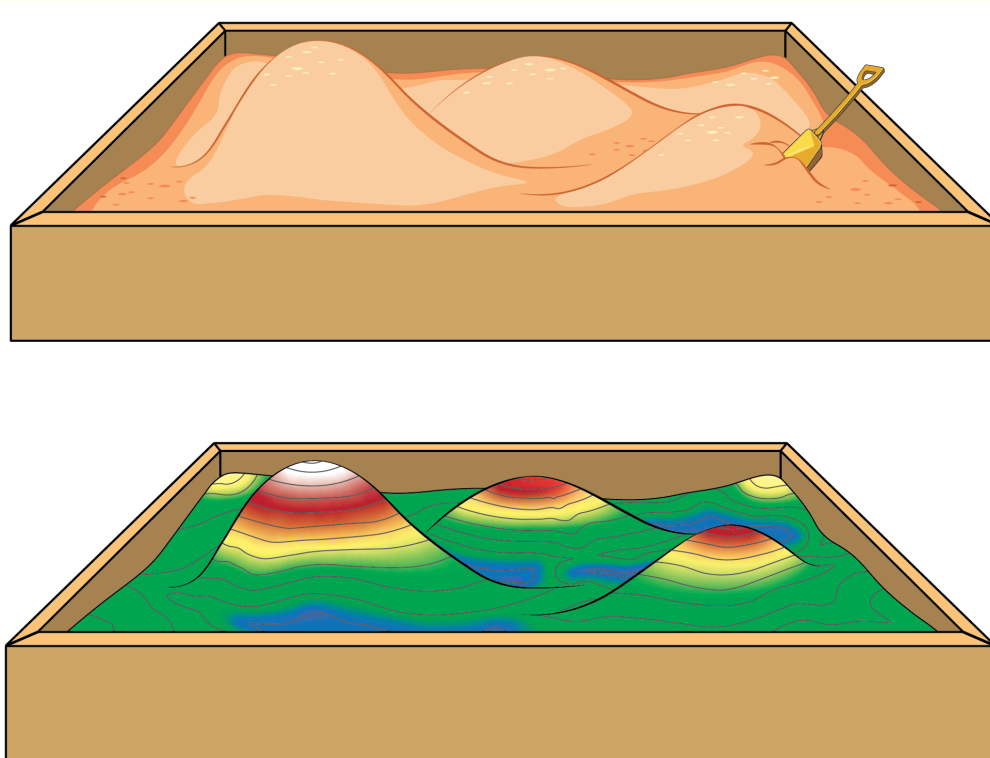


Figure 1.5 – Illustrations showing a sandbox with some mounds. The upper illustration is just the sand. The lower illustration shows an example of the projected image from the augmented reality sandbox. Image credit: Michael Comas, CC BY-NC-SA.

Make two features in the sandbox. On one side, make a tall hill with a steep side and a shallow side. On the other side, make a basin (a depression like a lake). Answer the following questions.

- What color is at the top of your hill? _____
- What color is at the bottom of your basin? _____
- What do the colors mean?

d. What do you think the lines represent?

e. Why are these lines closer together in some places and further apart in others?

f. Do the lines ever cross? Why or why not?

g. Hold out an open hand over the sandbox to create rain. How does the water flow?

1.5 Earth Properties: Density

Earth materials have a range of many properties. One important property is density. You will learn in lecture how the Earth has 3 major layers, each with a different density. Density is the mass of a substance per unit of volume. For example, water has a density of 1.0 g/cm^3 , which means that a cubic centimeter of water weighs 1 gram. Density is determined by the size, mass, and arrangement of atoms in a substance, but the density of a material also varies with temperature and pressure. This variation is typically small for solids and liquids but much greater for gases. Applying pressure on an object reduces its volume, consequently increasing its density. Raising the temperature of an object (with a few exceptions) increases its volume, consequently decreasing its density. Some Earth materials may also have fluid or gas in pore space which reduce their density. Some geoscientists measure the density of rocks either wet or dry.

Aside from three major layers in the Earth, there are other important physical processes that are a result of density differences. Some of them are related to heat such as the density of air and water controlling currents, clouds and circulation in oceans, lakes and our atmosphere. These then affect processes such as erosion, transport of sand, and the shape of Earth's landforms. So, density of Earth's materials is fundamental to many processes you will learn about this semester.

Exercise 1.8 – Density

Your instructor will place a bowling ball and a golf ball in a container of water.

- a. Do you think both balls are going to float or sink? Explain.

- b. What did you actually observe? Did it match what you thought would happen?

- c. Create a hypothesis to explain your observation.

The size of objects can be very deceiving when it comes to density. In many cases, our minds think that bigger objects will always sink in water, but that isn't always true. Take large cruise ships, for example.

It is easy to calculate the density of most objects, and we can do that with these materials.

density = mass/volume, $d = m/v$.

You can calculate the density of a sphere with the following equation: $C^3/6\pi^2$ where C is the circumference of the sphere that can be measured using string or tape.

- d. Measure the mass of the golf ball and bowling ball in grams (g). You may need to convert from kilograms (kg) to g.
- Mass of the golf ball: _____
 - Mass of the bowling ball: _____
- e. Before we can calculate the volume of a sphere, we need to know its circumference. Measure the circumference of the balls in cm.
- Circumference of the golf ball: _____
 - Circumference of the bowling ball: _____
- f. Calculate the volume of the ball in cm^3 using the following equation: $C^3/6\pi^2$ where C is the circumference.
- Volume of the golf ball: _____
 - Volume of the bowling ball: _____
- g. Now that you know the mass and volume of the balls, calculate the density of each in g/cm^3 .

- i. Density of the golf ball: _____
- ii. Density of the bowling ball: _____

Exercise 1.9 – Density of Earth Materials

Believe it or not, rocks on Earth have varying densities based on their chemical composition and structure. Your instructor has provided you with two examples of similar-sized rocks.

- a. What differences do you notice between the two rocks?

- b. Does one rock feel heavier than the other? _____

- c. Let's figure out the density of these rocks. Remember that density = mass/volume. ($d=m/v$). You can get the mass by weighing your rocks on a scale (Figure 1.6). Record the mass in grams for each rock.

- i. Mass of rock 1 _____
- ii. Mass of rock 2 _____

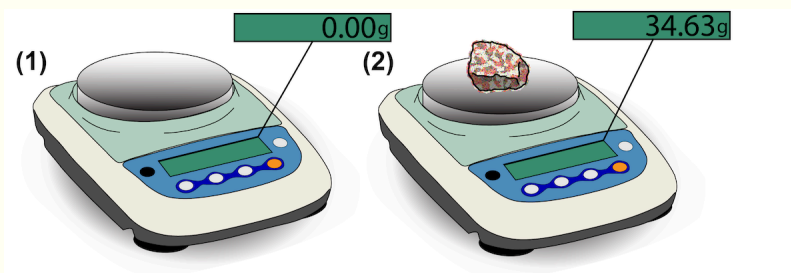


Figure 1.6 – Measuring the mass of a rock. Image credit: Michael Comas, CC BY-NC-SA.

- d. You can determine the volume of your rocks by measuring how much water is displaced in a container when you place the rock in it (Figure 1.7). Fill a graduated cylinder with water. It's recommended you fill it to a milliliter value that is easy to work with, like 100 ml. Remember to measure from the bottom of the meniscus. Now, place one of your rocks in the graduated cylinder. You'll notice the water level rise; that's because the rock is displacing the water, and the amount of that displacement is equal to the volume of the rock. Measure this new volume of water. Subtract your starting volume from the new volume to determine the volume of your rock.

- i. Volume of rock 1 _____
- ii. Volume of rock 2 _____

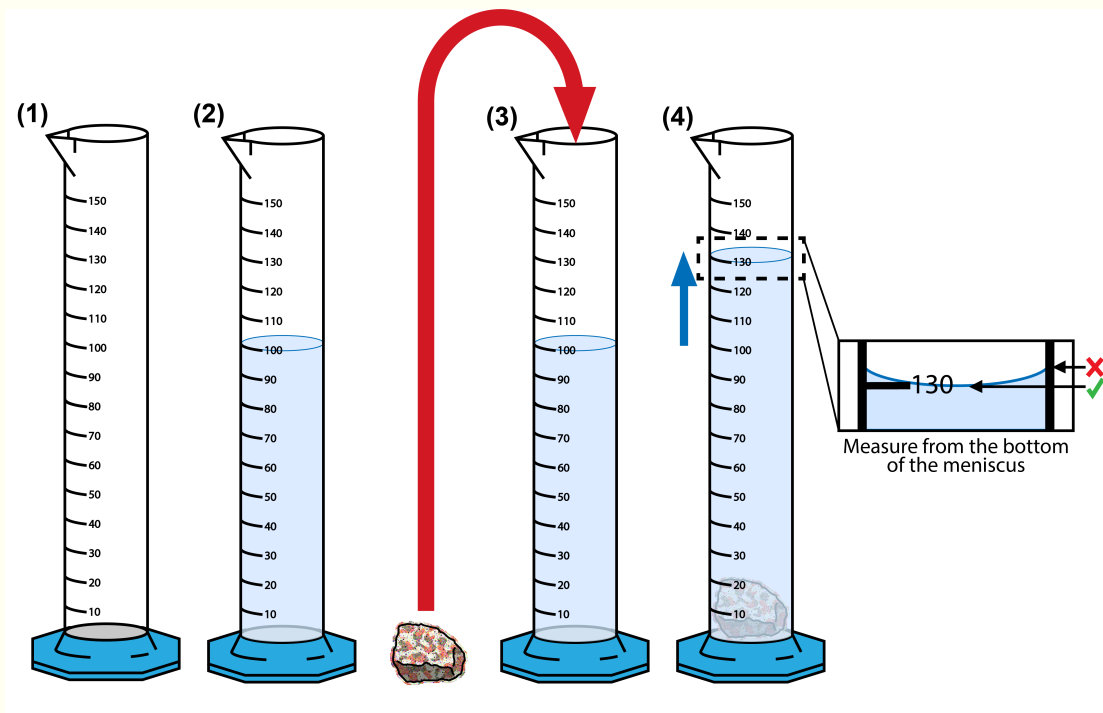


Figure 1.7 – Procedure for measuring the volume of a rock. Image credit: Michael Comas, CC BY-NC-SA.

e. Now, determine the density of your rocks ($d=m/v$). The unit for density is g/cm^3 , $1 \text{ ml} = 1 \text{ cm}^3$.

i. Density of rock 1 _____

ii. Density of rock 2 _____

f. Why do you think there is a difference in density between the two rocks?

g. **Critical Thinking:** Do you think these rocks formed in the same setting? Explain your reasoning.

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson, Michael Comas, Somaria Sammy

CHAPTER 2: TOPOGRAPHIC MAPS

Latitude, longitude, directions, and contour lines

Learning Objectives

The goals of this chapter are to:

- Recognize different coordinate systems
- Read a compass
- Interpret topographic lines
- Explain topographic maps and profiles

2.1 Coordinate Systems

An important part of geologic field work is noting the precise locations of samples, outcrops, geologic features, etc. If you or other scientists cannot return to find your exact study site, then the science cannot be reproduced. Part of being a scientist is creating data, an experiment, etc. that is reproducible.

In Chapter 1 you briefly explored the different coordinate systems for maps: Degree Minutes Seconds (DMS) and Decimal Degrees (DD). Which system you use may depend on how you keep track of your study sites. That means it's important to not only understand different coordinate systems but also be able to convert coordinates between systems.

DMS divides the roughly spherical planet Earth into 360 slices that are each 1° , each degree is broken down into 60 smaller slices called minutes, and each minute is broken into 60 smaller slices called seconds. DD converts the three numbers used to define a coordinate with DMS into a single number using a simple calculation.

Exercise 2.1 – Converting Geographic Coordinates

Figure 2.1 shows you how to convert a single coordinate back and forth between DMS and DD.

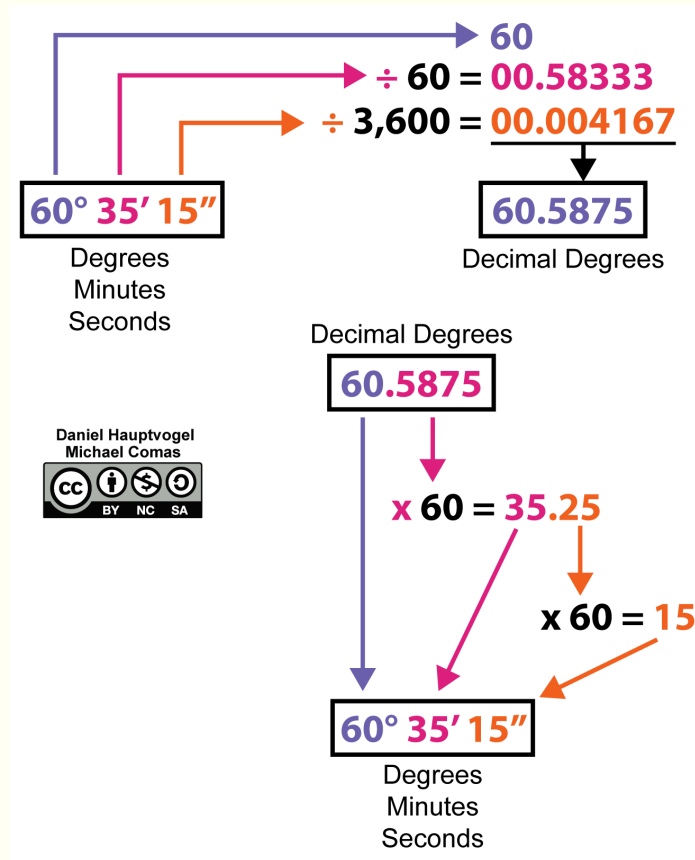


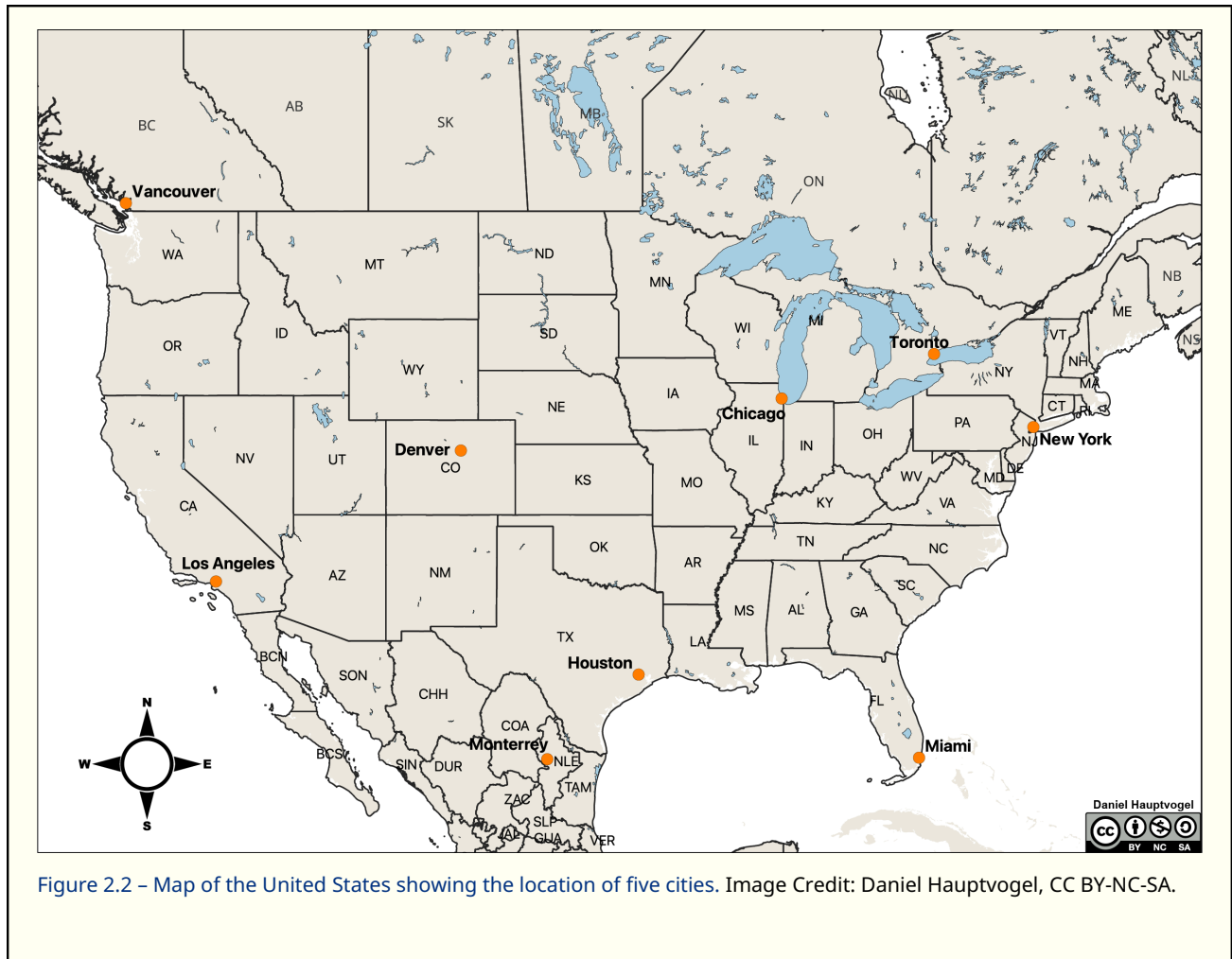
Figure 2.1 – Flow chart for converting geographic coordinates between DMS (degrees, minutes, seconds) and DD (decimal degrees). Image credit: Michael Comas, CC BY-NC-SA 4.0.

- a. Table 2.1 contains geographic coordinates for some cities, as shown in Figure 2.2. One of the coordinate systems is given for each city. Using Figure 2.1, convert coordinates to either DMS or DD. Denver, CO has been done for you.

Table 2.1 – U.S. cities and their geographic coordinates

	Degrees Minutes Seconds (DMS)	Decimal Degrees (DD)
Denver, CO	39° 44' 21" N, 104° 59' 25" W	39.7392 N, 104.9903 W
New York, NY	40° 42' 46" N, 74° 00' 22" W	
Los Angeles, CA		34.0549 N, 118.2426 W
Monterrey, Mexico		25.6866 N, 100.3161 W
Chicago, IL	41° 51' 55" N, 87° 37' 40" W	
Houston, TX	29° 45' 46" N, 95° 22' 59" W	
Toronto, Canada		43.6532 N, 79.3832 W

- b. Which coordinate system do you think is better and why?



2.2 The Compass

An important part of reading maps is understanding how to use a **compass**. As a geologist, you may want to know the direction a rock unit is dipping, the direction from one mountain peak to another, or the direction a paleo-river used to flow. There are two forms of direction that you should be familiar with: the cardinal directions and azimuth system (Figure 2.3). Cardinal directions refer to north, east, south, and west and can be divided even further into intercardinal (NE, NNE, ENE, etc.). Generally speaking, when we say something is to the north, we don't always mean that it is directly north. It's more likely a little bit northeast or northwest. That's where azimuth comes in. Azimuth is the angular measurement from a compass, up to 360°

Direction	Azimuth
N	0°
NNE	22.5°
NE	45°
ENE	67.5°
E	90°
ESE	112.5°
SE	135°
SSE	157.5°
S	180°
SSW	202.5°
SW	225°
WSW	247.5°
W	270°
WNW	292.5°
NW	315°
NNW	337.5°

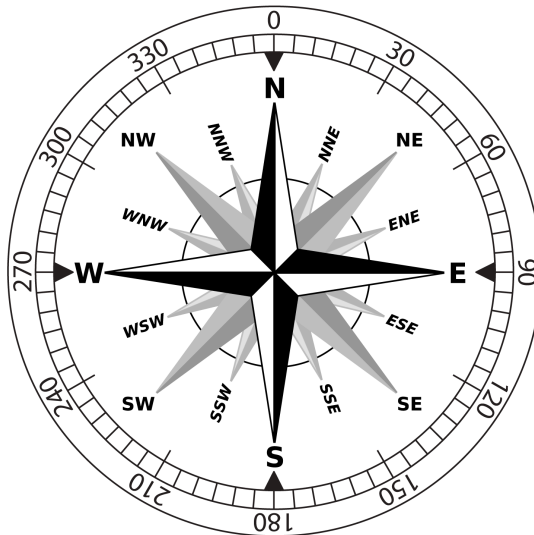


Figure 2.3 – Compass directions using cardinal and azimuth systems.
Image credit: Daniel Hauptvogel and Michael Comas, CC BY-NC-SA.

Exercise 2.2 – Exploring Compass Directions

Practice your directions by using the cardinal and azimuth systems to answer the following questions.

- Without using a protractor, what is the cardinal direction (NW, WNW, E, SE, etc.) between the following cities in Figure 2.4 (Houston to Austin example completed for you)?
 - Houston to Austin: WNW
 - El Paso to Santa Fe: _____
 - Santa Fe to Dallas: _____
 - Dallas to Torreon: _____
 - Torreon to Matamoros: _____

Follow the steps below to find the direction (azimuth) between cities in Texas in Figure 2.4. An example has been provided along with the steps for determining the azimuth from Houston to Austin.

- Use a straight edge to draw a line between your two points
 - Place the cross of the protractor on your starting point and orient the 90° mark on the protractor towards the north if the second point is to the north or towards the south if the second point is to the south.
 - Determine how many degrees away from 0 your line is pointing.
- Now, use a protractor and find the azimuth directions for the cities below (Houston to Austin example completed for you).
 - Houston to Austin: 285°
 - Matamoros to Austin: _____
 - Austin to Chihuahua: _____
 - Chihuahua to Amarillo: _____

v. Amarillo to Houston: _____

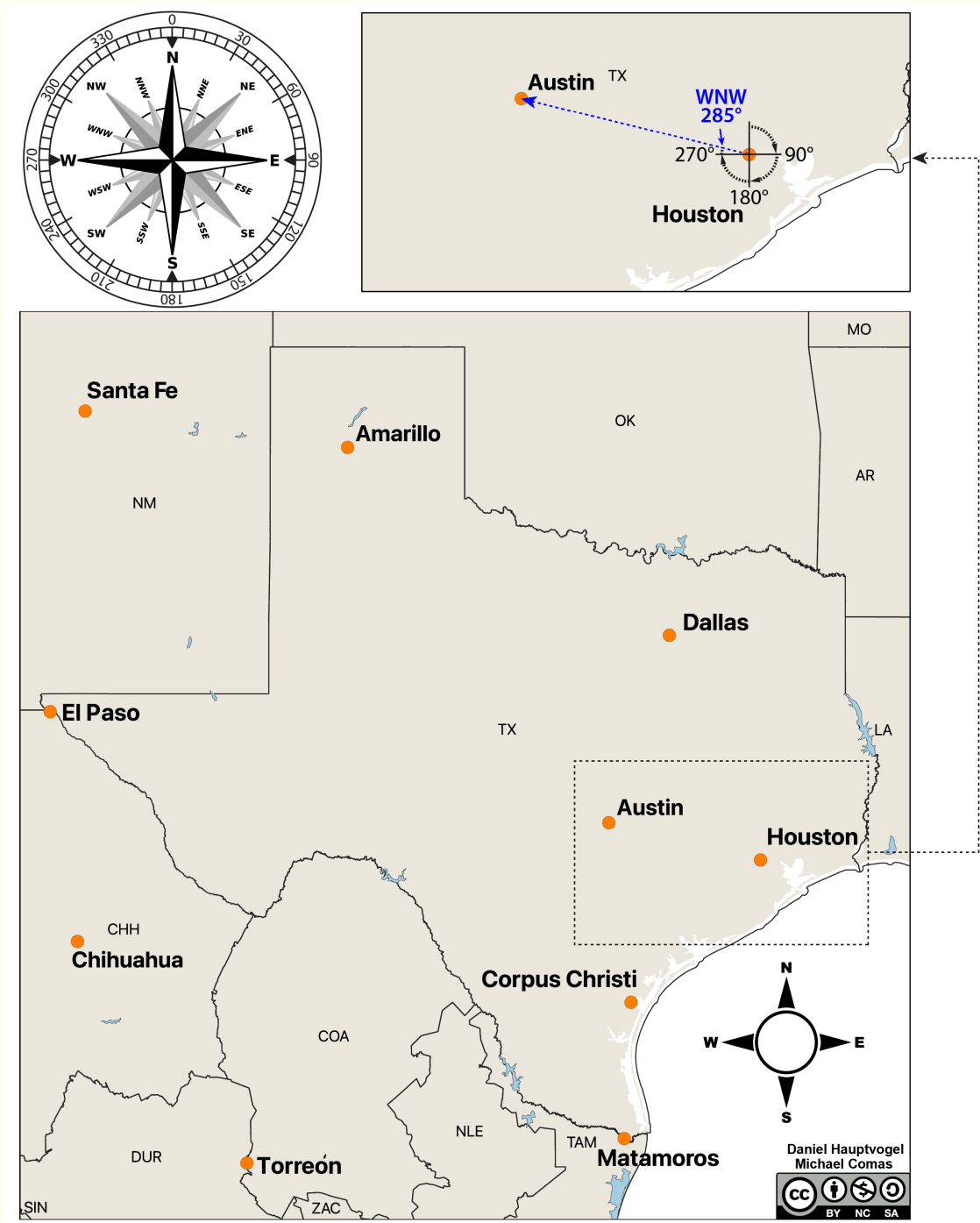


Figure 2.4 – Map showing the locations of major cities in Texas and northern Mexico. Inset map is an example of using a protractor to determine azimuth compass direction. Image credit: Daniel Hauptvogel and Michael Comas, CC BY-NC-SA.

2.3 Map Scales

Maps are scaled-down versions of the areas they represent. The word “scale” refers to the amount of reduction the map represents. All maps include at least one type of map scale to indicate the relationship between the area on the map and the area of the region it represents in reality. Map scales are provided so that a map reader can determine exactly how much distance is actually represented on their map, or to measure the distance between two points on a map, or even to calculate the gradient (slope) of a hill, valley, or river.

The two commonly used map scales on a **topographic map** are the bar scale and the fractional scale (also known as the ratio scale). A common ratio scale used in topographic maps is 1:24,000, which means that 1 unit of measurement on the map is 24,000 units in reality. The unit does not matter because the principle works the same for all units; it could be inches, feet, centimeters, etc.

Exercise 2.3 – Using Map Scales

You can use your knowledge of scales to estimate distances on maps.

- On a map with a scale of 1:12,000, how long is a stream (in feet) that measures 1 inch on the map?

- On a map with a scale of 1:40,000, how long is a road (in meters) that measures 5 cm on the map?

- Your instructor will provide you with two maps of the Galveston, TX region at different scales. One was published in 1983, the other in 2022. What are the scales of each map?

- Look closely at both maps. What information is given on the 2022 map that isn't on the 1983 map, and vice versa?

- On the northeast side of the 2022 map, measure the channel width between Galveston Island (Fort Point) and Point Bolivar. How wide is the channel on the map (cm) and in reality (m and mi)?

- Do the same measurements using the map from 1983.

- Which map is better for determining this distance? Why?

- h. These maps were published 39 years apart. Can you think of any reason why this may have affected your measurements?

- i. Do you think it is important that maps be updated often? Should certain geographic regions be re-mapped more often than others? Why?

- j. Which map would be best to use to show the projected approach of a hurricane toward the Texas coast? Why?

- k. Which map would best display detailed hurricane evacuation routes off of Galveston Island. Why?

- l. Which map should a cruise ship captain use to help guide him into the port at Galveston? Why?

2.4 Contour Lines and Topographic Maps

Topographic maps show the topography of the landscape, including hills, mountains, valleys, rivers, etc. These maps contain **contour lines**, which are lines of equal elevation. That means everywhere along that line will have the same elevation.

Elevations for major contour lines are typically marked on the line. To avoid clutter, not every contour is labeled. The elevation of an unlabeled contour line can be determined by knowing the contour interval and looking at adjacent contour lines. The elevation of a point located in between two contour lines can be estimated by interpolating between the lines. If a point is halfway between two contour lines, it will be about halfway between the elevations of those two contour lines.

In the US, topographic maps have elevation marked in feet or meters above mean (average) sea level. International maps and maps of elevation of the ocean floor (bathymetry) are usually marked in meters.

Exercise 2.4 – Contour Lines and Topographic Maps

Capulin Volcano in New Mexico (Figure 2.5) is a volcanic cinder cone that is about 60,000 years old. Figure 2.6 is a map view and topographic map of the volcano.



Figure 2.5 – Side view of Capulin Volcano in New Mexico. Image credit: Google Earth

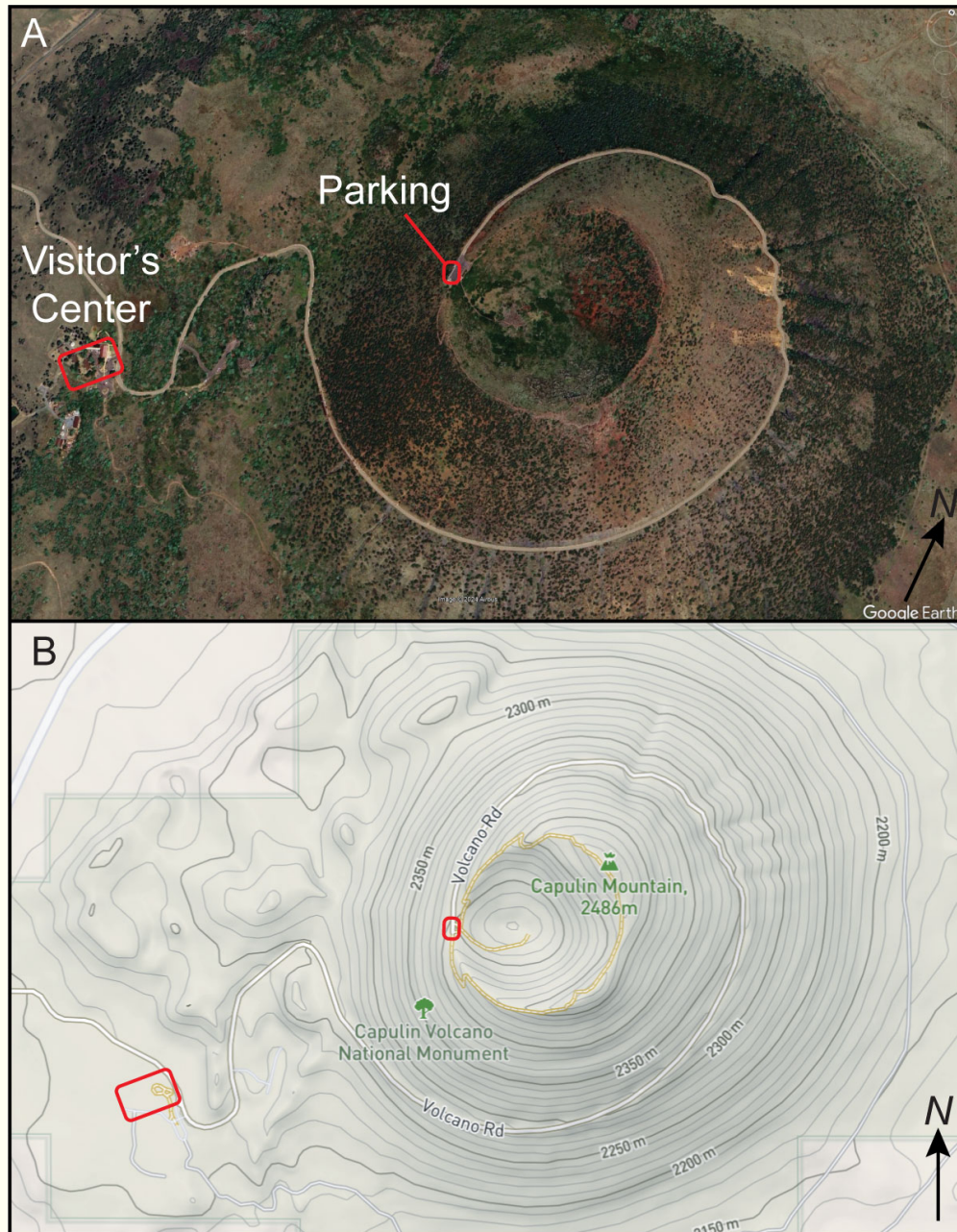


Figure 2.6 – A: Map view of Capulin Volcano. B: Topographic map of Capulin Volcano. Image credit: A: Google Earth; B: USGS.

- a. What pattern do you notice in the contour lines that represent the volcano?

- b. A contour interval is the elevation difference between contour lines. Some lines are bold; these are major contours and are marked at regular intervals. On this map, the major contours are 50 m apart. What is the contour interval of this map? _____

- c. What is the elevation of the highest point of Capulin Volcano? _____
- d. How deep is the crater of the volcano? _____
- e. If you either walk or drive from the visitor's center to the scenic overlook, how much would your elevation have changed? _____
- f. Topographic maps also give you a sense of the slope of the landscape. Examine the eastern and western sides of Capulin Volcano. Which side is steeper, and which is shallower? What does the spacing of the contour lines tell you about the slope?

- g. Construct a topographic profile of this area in Google Earth. Your instructor will help you.

Rules

The rules inherent in topographic maps are pretty simple: contours represent lines of equal elevation, contours always close (except on the edge of a map), contours never cross, although they may become very close on steep terrain or cliffs, closely spaced contours represent steepness, and the geometry of contours changes in predictable ways between valleys and ridges. When contour lines cross a river or valley, the line forms a "V" shape. The open side of the V is towards lower elevation/downstream, and the point of the V points towards high elevation/upstream. This is called the Rule of V's.

Exercise 2.5 – Exploring Rules of Contour Lines

Below is an image from the high peaks of the Sierra Nevada and a simplified topographic map of this area. Use these to discover some other rules of topographic maps. Examine the photo and map in Figures 2.7 and 2.8.



Figure 2.7 View of Tulainyo Lake from the summit of Mt. Russell looking towards the Inyo Valley to the northeast. The small lake to the west of Tulainyo Lake is not visible in this photo. Also shown on the right is the “Cleaver” and to the left is the summit of Tunnabora Peak (not shown in topographic map). Mt. Russell is 14,094 ft (4,296 m) and is 17th highest point in California. Image source: [Penitentes](#) CC BY-SA.

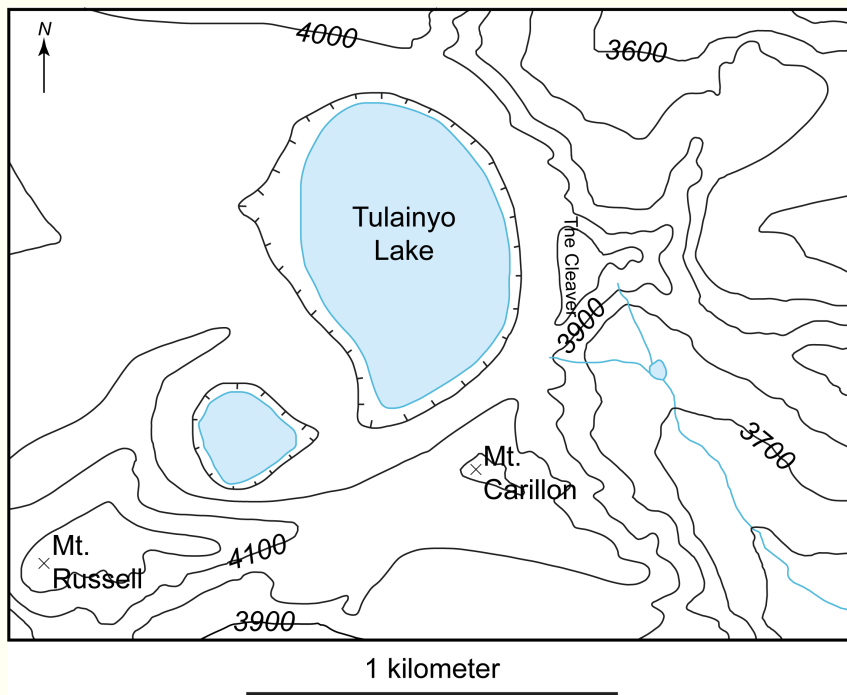


Figure 2.8 – Simplified topographic map of the Tulainyo Lake region with 100 m contour intervals. Blue lines and areas indicate water bodies (lakes and streams). The contour interval is 100 m (328 ft). Image credit Virginia Sisson adapted from USGS.

- a. Look at the stream in the southeastern side of the map. What happens to contour lines when they cross a stream? Your instructor may also provide you with block models to illustrate this rule.

- b. Tulainyo Lake and an unnamed lake in this map have little hatch marks around them. What do these mean?

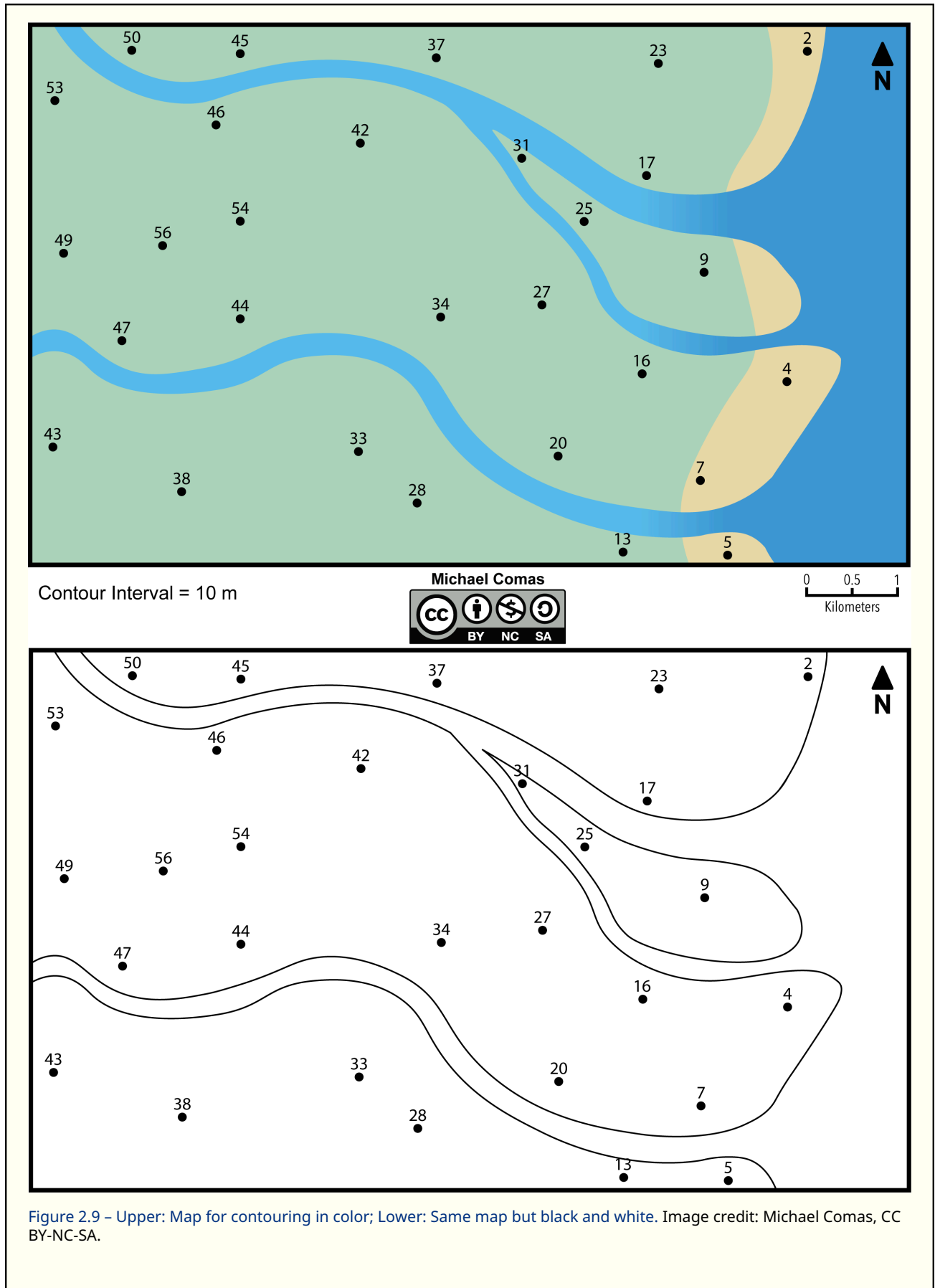
- c. Do the contour lines ever cross each other? Why or why not?

- d. Where are the lowest and highest elevations in this map? _____

- e. What do the cross marks indicate for Mount Russell and Mount Carillon?

- f. Critical thinking: The contour interval is 100 m (328 ft). Do you think this is adequate to show the topography in this region (look at a photo of the area). What contour interval would you prefer and why?

- g. Build your own contour map. Use the elevation data to make your own contour map from the data in Figure 2.9. The contour interval will be 10 m. The zero-contour interval is at sea level; so, you don't need to draw that one! You may have to interpolate and extrapolate the data as there are very few data points that are 10 m intervals. Remember how the contour intervals should look around the small streams and rivers. Draw your contour lines so that they are continuous: they will either continue to the edge of the map or form an enclosed circle.



Exercise 2.6 – Exploring the Augmented Reality Sandbox

Your instructor will bring you to the augmented reality sandbox.

- a. Create a ridge (a narrow, linear mountain) with the sand. Make one side of the ridge shallow and the other steep. Sketch what the contour lines look like and identify your shallow side and steep side. Use a contour interval of 50.
- b. Place an open hand above the top of the ridge to create rain. Describe how the water flows.

- c. Now, create a valley in the middle of the sandbox so that elevation increases on either side. Sketch what the contour lines look like. Use a contour interval of 20.
- d. Use your open hand to make it rain. Describe what happens to the water.

- e. Recreate the topographic map from Figure 2.10 in the sandbox.

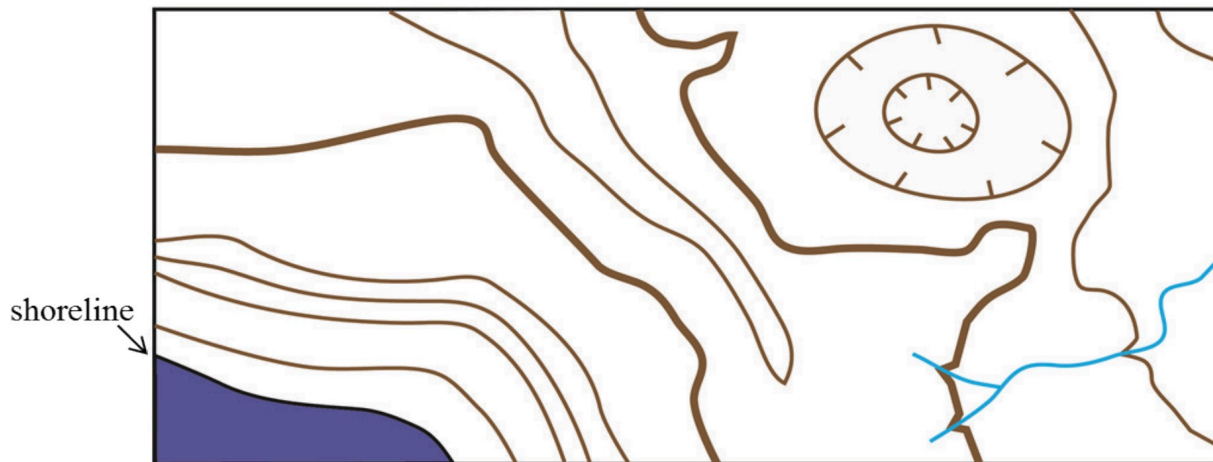


Figure 2.10 – A topographic map of an area. Image credit: Brad Deline, CC BY-SA.

Most of now use our cell phones with built in GPS, maps and apps to help us decide where to go. Even with these, you hear stories of people blindly following these and ending up on roads that dead end or are closed due to weather. Or you may go someplace without cell signal to be able to use your map app. So, knowing how to read a topographic map, is a useful skill for these and other situations.

Exercise 2.7 – Navigating with a Topographic Map

You and your friends are planning a hiking trip through Enchanted Rock State Natural Area (Figure 2.11). All the camping spots near the main parking lot are reserved. So, instead your group wants to camp in a backcountry at either Moss Lake or Walnut Springs. Some of your friends also want to go rock climbing.

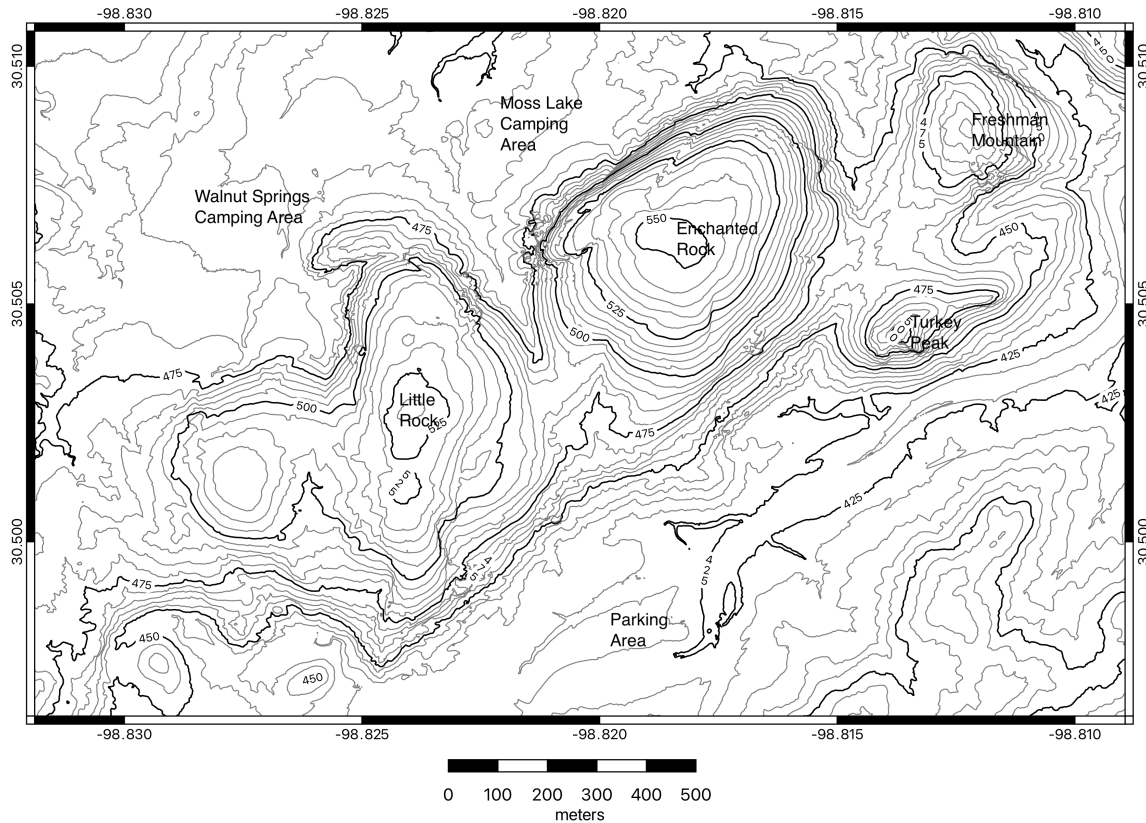


Figure 2.11 – Topographic map of Enchanted Rock State Natural Area with 5 m contour intervals. Also shown are main parking lot and two backcountry camp grounds. Image credit: Daniel Hauptvogel CC BY-NC-SA, data from USGS.

a. Estimate the elevation for the following points:

- i. Enchanted Rock: _____
- ii. Little Rock: _____
- iii. Parking Lot: _____

b. There are two possible back country camp grounds at either Moss Lake or Walnut Springs. Chose one for your group. Draw two possible routes to this back country camping area from the parking lot. What is the length for each route?

- i. A: _____
- ii. B: _____

c. What is the elevation gain for each route:

- i. A: _____

- ii. B: _____
- d. Which trip route would you take? A or B? Explain your reasoning.

- e. You and your friends decide to hike to the top of Enchanted Rock. Since the entire dome is just rock, you can go almost anywhere to get to the top. You want to take the path with the lowest slope because it will be easier. Draw the best path to take on Figure 2.11.
- f. You and your friends want to go rock climbing (Figure 2.12). They think there are several possible places with very steep topography. Which place has the steepest topography? Circle it on Figure 2.11.

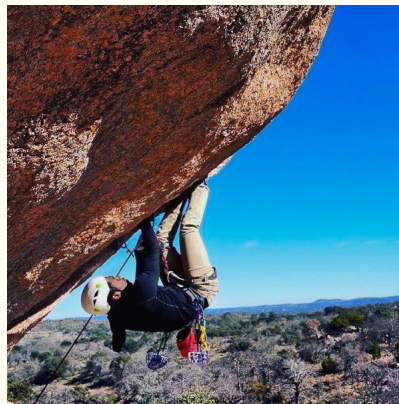


Figure 2.12 – Rock climbing near Freshman Mountain at Enchanted Rock State Natural Area. Image credit: [Caitlin McNulty](#) CC, enhanced by Alex Maze.

2.5 Topographic Profiles

To get a good sense of the landscape, geologists construct topographic profiles (Figure 2.13). To do this, use these five steps:

1. Place a strip of paper along the line of the profile you are making (W-E) and label the starting and ending points (Figure 2.13).
2. Mark the paper where it comes into contact with any contour lines and label each mark with the corresponding elevation.
3. Choose your vertical scale and prepare a sheet of graph paper by labeling the vertical axis according to the scale you have chosen. It is typically best to choose a range of elevations that encompass your profile elevations (for example, if the Volcano's elevations ranged from 223-339 meters, it may be best to choose a scale from 200-350 meters).
4. Place your strip of paper with the labeled marks (from Step 2) at the bottom of the vertical scale and use the elevation data to plot points on your graph.
5. Trace the points from one side of the profile to the other.

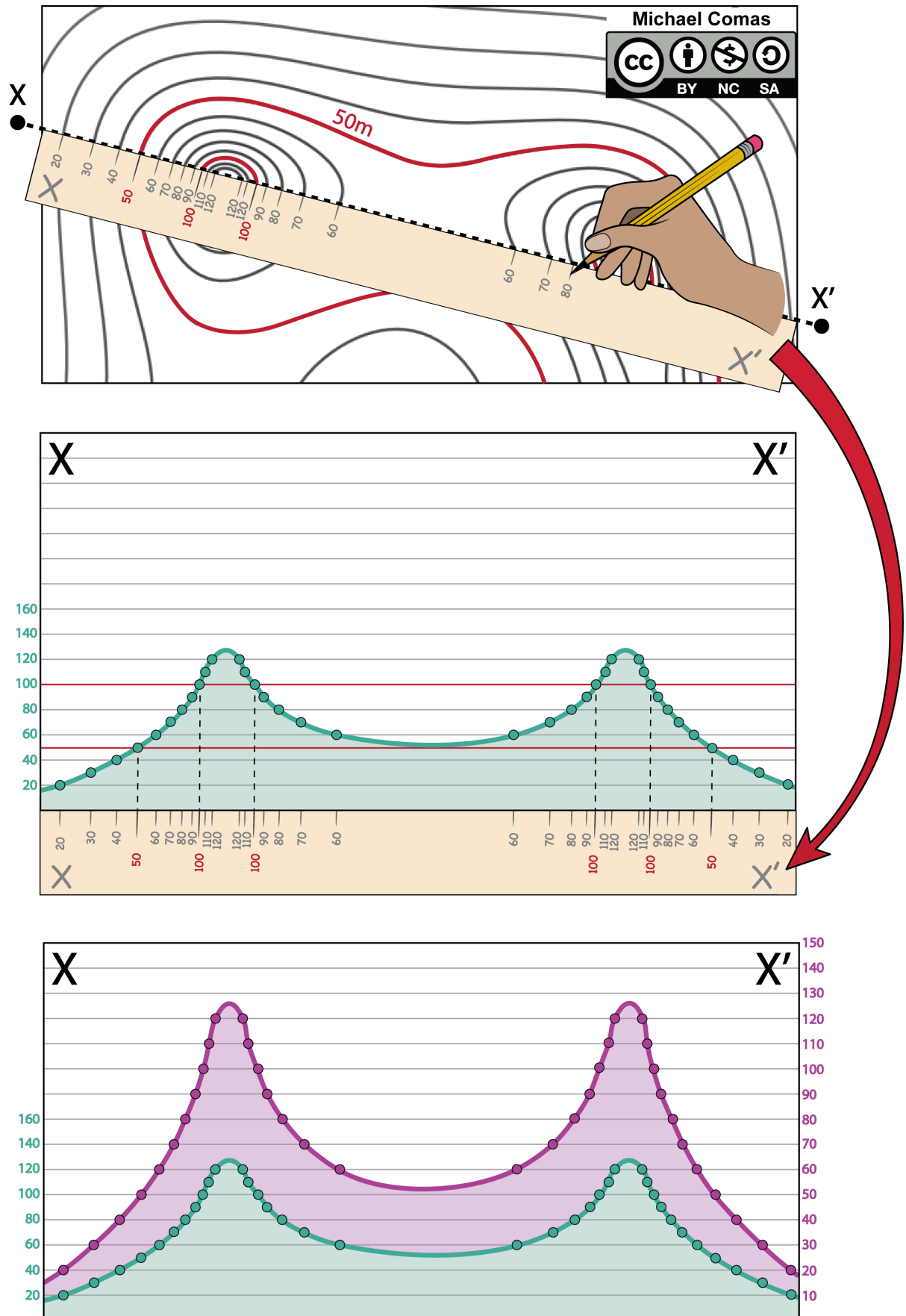


Figure 2.13 – How to construct a topographic profile. Image credit: Michael Comas, CC BY-NC-SA.

Exercise 2.8 – Constructing a Topographic Profile

Make a topographic profile for Figure 2.14.

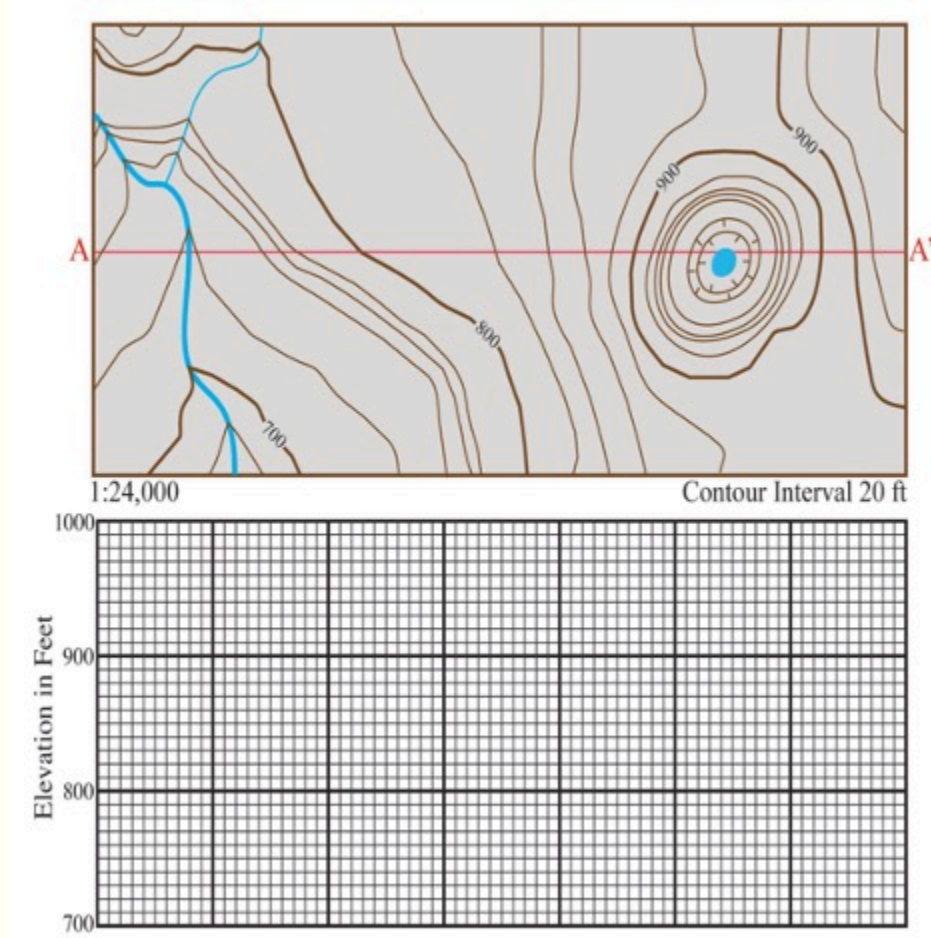


Figure 2.14 – Topographic map of a region. Image credit: Sean Lacey (2018) CC BY 4.0, after Brad Deline (2017) CC BY-SA.

Additional Information

Exercise Contributions

Michael Comas, Daniel Hauptvogel, and Virginia Sisson

CHAPTER 3: PLATE TECTONICS

Boundaries and Earth's Structure

Learning Objectives

The goals of this chapter are to:

- Identify types of plate boundaries and compare their characteristic earthquake and volcanic activities
- Assess the basic lines of evidence supporting plate tectonics
- Use Earth features to explore the drivers of plate tectonic motions

3.1 Introduction

Plate tectonics is the grand unifying theory in geology. It gets that title because many topics in geology can be explained, in some way, by the movement of tectonic plates. Tectonic plates are composed of Earth's crust and the uppermost, rigid portion of the mantle. Together, they are called the lithosphere.

Exercise 3.1 – Discovering Plate Boundaries

A team from the world-renowned EAS research group (Earth and Atmospheric Sciences) has won a multimillion-dollar government contract to examine the latest information about the Earth and develop hypotheses about how our planet has evolved. You have been hired to analyze sets of observational data to determine if there is any link between them.

Break up into four groups. Each group has a specialty, and your instructor will give you one of the following maps:

- Seismology (earthquakes)
- Volcanology (volcanoes)
- Physiography (topography)
- Geochronology (age of rocks)

Examine the map in your specialty group and answer the following questions.

- What is your specialty? _____
- What do the colors and/or symbols on your map mean?

- c. Examine your map and describe at least three patterns you see in the distribution of your data (for example, there is a linear chain of volcanoes on the west coast of South America).

Now, get into four new groups. These new groups must have at least one member from each specialty. Each specialist should explain what their map shows and describe the three map patterns they identified.

- d. Compare all four maps and identify patterns or relationships between them. These can be between two, three, or all four of the maps. Make at least five observations.

Select one person from your group to inform the class on the patterns you identified amongst the maps.

- e. What similarities did the other groups find that were the same as yours?

- f. What similarities did other groups find that yours didn't?

- g. It has been suggested that Earth's surface features are broken into fragments called lithospheric plates that fit together like pieces of a jigsaw puzzle. From your observations and those of your EAS colleagues, draw lines on the world map in Figure 3.1 that might outline major plate boundaries.

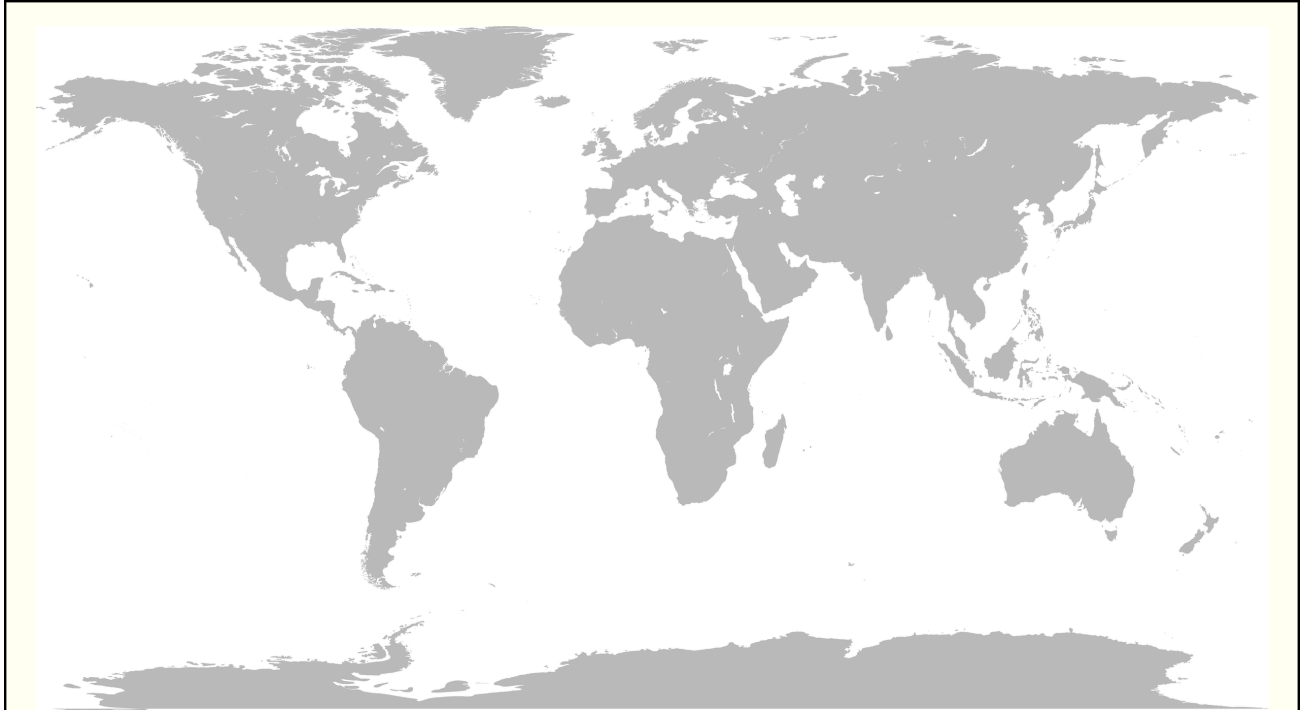


Figure 3.1 – Map of the world. Image credit: Wikimedia user [Crates](#), CC BY-SA.

This exercise is inspired by [Dale Sawyer's Discovering Plate Boundaries exercise](#).

3.2 Plates, Crust, and Lithosphere

In Exercise 3.1, you discovered the Earth's surface is broken into pieces called **tectonic plates**. You also began to see the relationship between earthquakes, volcanoes, topography, seafloor age, and plate tectonics. These plates move across the Earth's surface, and the boundaries between plates vary depending on whether plates are moving apart (divergent), coming together (convergent), or moving alongside one another (transform). Along these plate boundaries is where you find most of the world's earthquakes.

Geologists divide the Earth into either physical or compositional layers (Figure 3.2). The compositional layers include crust, mantle and core. Whereas the physical layers include the lithosphere, asthenosphere, outer core and inner core.

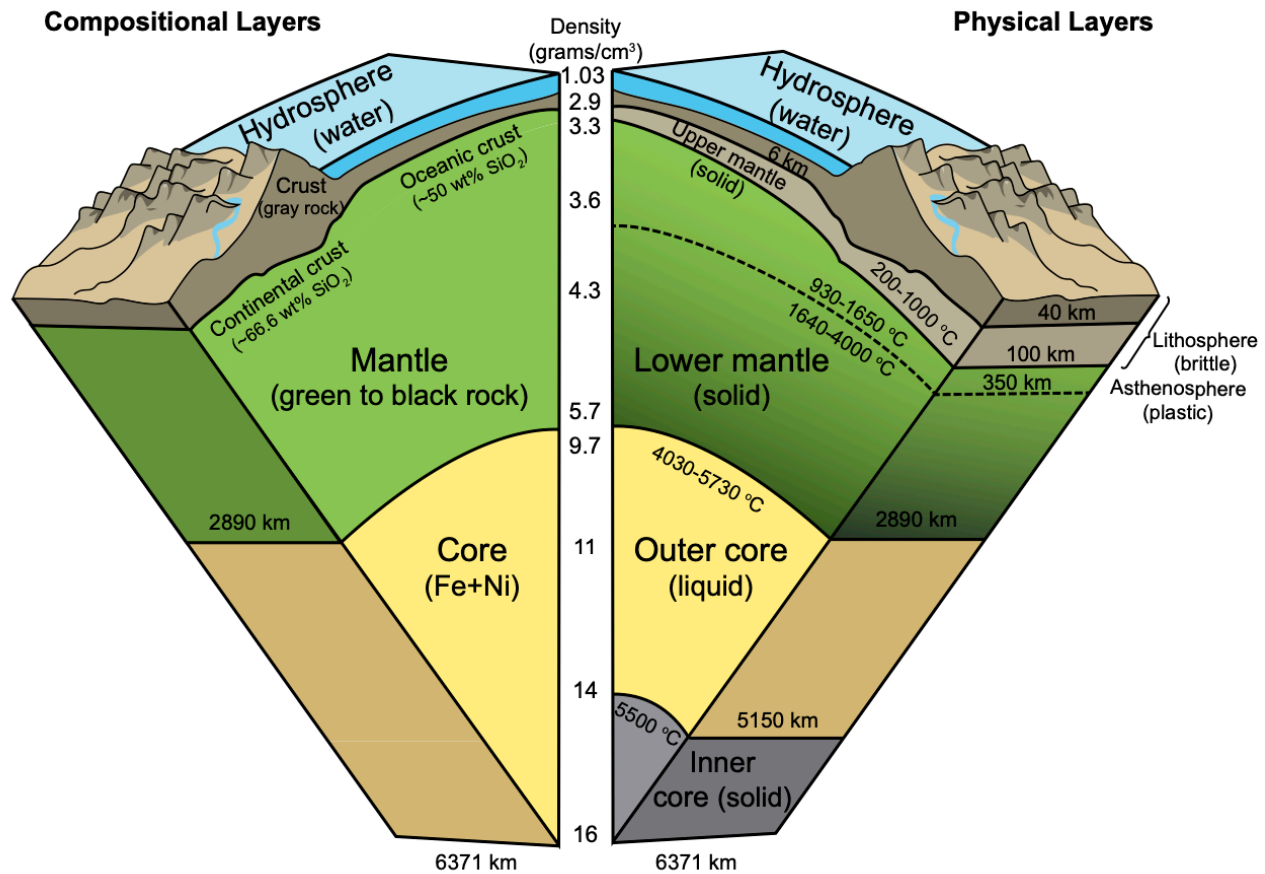


Figure 3.2 Two schematic cut-away views through the Earth showing its internal structure with compositional layers on left and physical layers on right. Note that the layers at the top of each slice are not to scale. They are vertically exaggerated so that you can see the features. Image Credit: Virginia Sisson CC BY-NC-SA.

Tectonic plates are also called the **lithosphere**, which is Earth's crust and the uppermost solid part of the mantle. The crustal portion has two different compositions, oceanic and continental (Table 3.1). The lithosphere sits on top of a weaker portion of the mantle, called the **asthenosphere**, which allows the lithosphere to move (i.e., plate tectonics)

Table 3.1 – Comparison of oceanic and continental crust

Property	Oceanic Crust	Continental Crust
Thickness	5-10 km	25-80 km
Density	3.0g/cm ³	2.7g/cm ³
Silica (SiO ₂) Content	50%	66.6%
Composition	Fe, Mg, and Ca silicates	K, Na, and Al silicates
Color	Dark	Light

Exercise 3.2 – Exploring Plates and Plate Boundaries

Use Figures 3.2 and 3.3 to answer the following questions

- a. Provide a detailed description of what Figure 3.2 shows and what the colored lines mean.

- b. Which type of plate boundary is most abundant? _____

- c. On which plate does the mainland United States including Alaska reside? _____

- d. Where is the eastern edge of this plate? _____

- e. What type of lithosphere makes up this plate? _____

- f. Are there any other plates that have a similar makeup? If so, name them. _____

- g. Compare and contrast the plate tectonic settings of the Atlantic and Pacific Oceans. Look at the boundaries within the oceans and on their margins.

- h. Look at the map of volcanoes in Figure 3.3 and compare that to the types of plate boundaries in Figure 3.2. Come up with an explanation about the location of most volcanoes as they relate to plate tectonics.

- i. **Critical Thinking:** When comparing the Atlantic and Pacific Oceans, which one do you think is getting bigger and which is becoming smaller? Explain your answer.

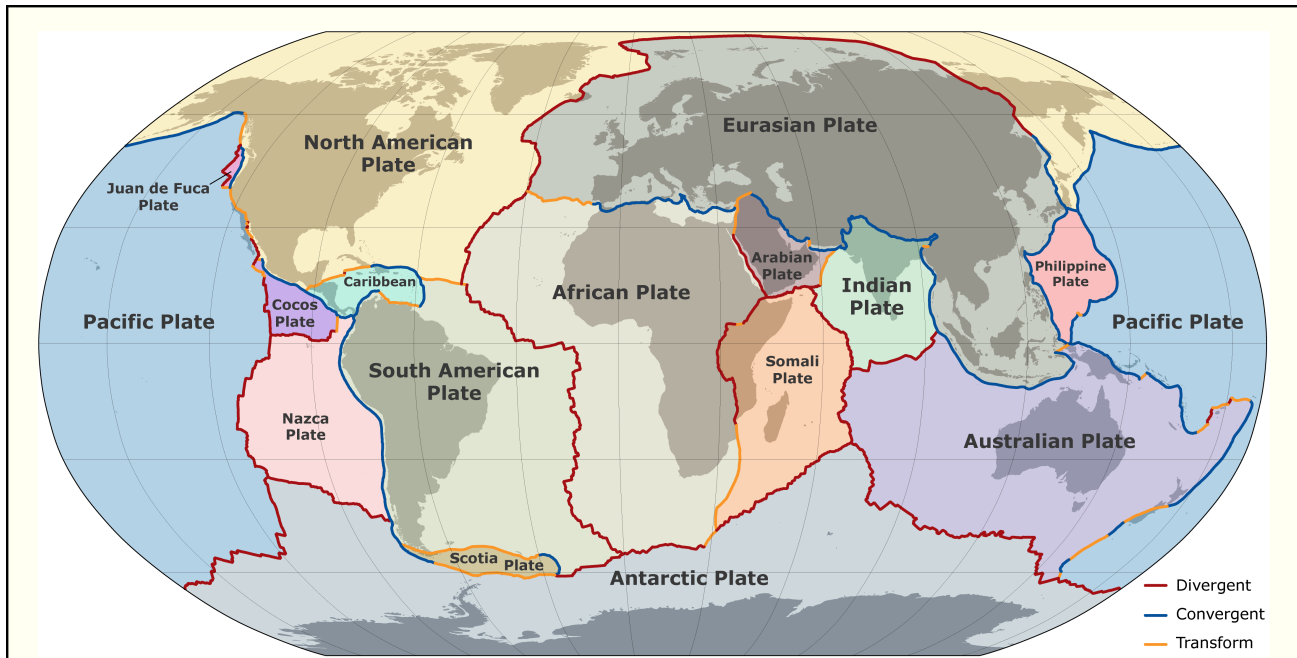


Figure 3.2 – Plate tectonic map of the world showing the major tectonic plates. There are other plates in more complex regions of the world, particularly in the western Pacific Ocean. Image credit: modified from [wikimedia user M.Bitton, CC BY-SA](#).

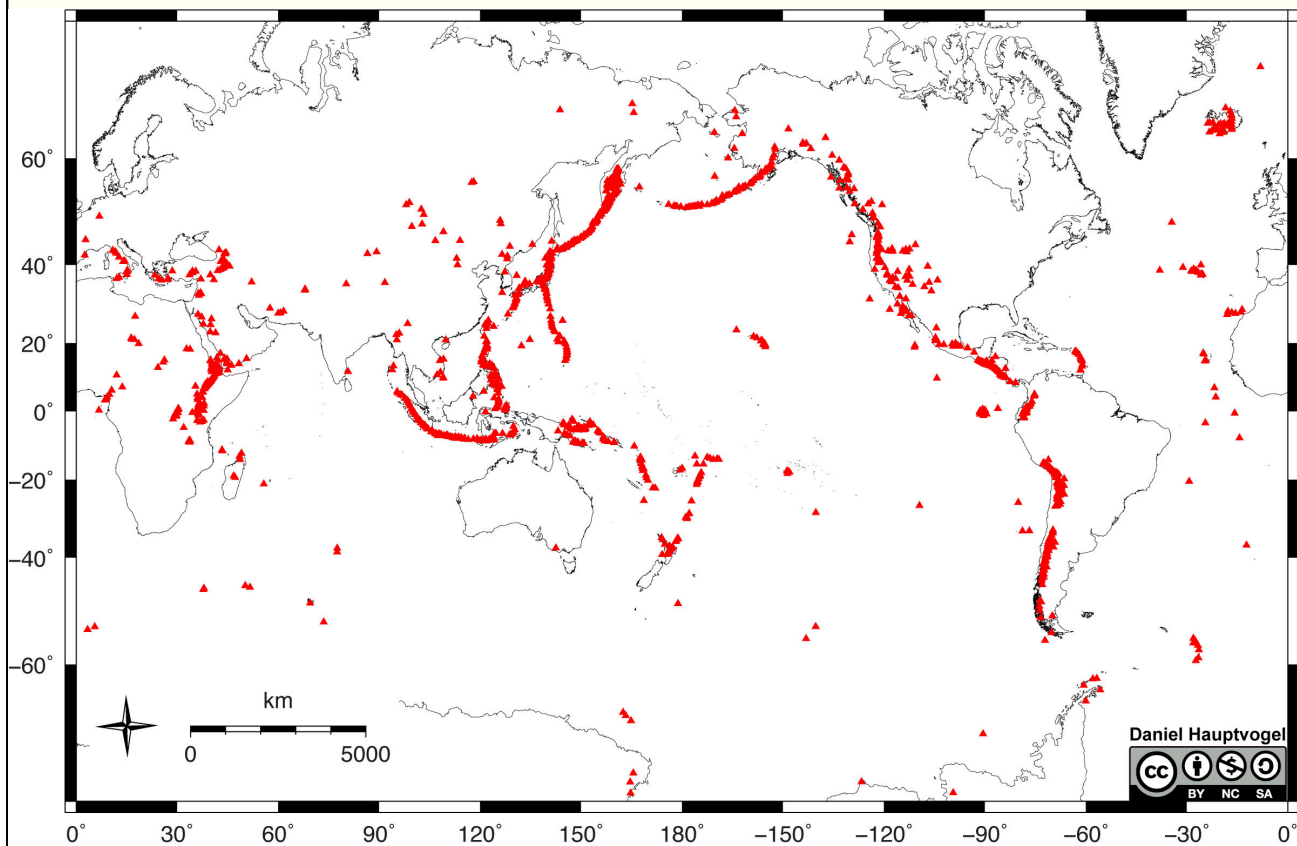


Figure 3.3 – This map shows the location of volcanoes that have been active within the past 10,000 years (red triangles). Map scale reference is 30° latitude. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

3.3 Subduction Zones

When oceanic lithosphere is part of a convergent boundary, it will sink and descend into Earth's mantle due to the difference in density, a process called **subduction** (Figure 3.4). This happens in collisions between two oceanic plates, oceanic-continental plates, and continent-continent collisions. In an oceanic-oceanic collision, the denser of the two oceanic plates, which is usually the older plate, will subduct.

It is a common misconception that the subducting plate will melt to create magma. The truth is that the downgoing plate is still too cold to melt, and it takes a very long time to heat up enough to begin melting. What really happens is as the subducting plate descends, water from the oceanic slab is driven off and enters the asthenosphere directly above it. This water lowers the melting point of the asthenosphere and causes part of it to begin melting. The newly created magma then rises toward the surface, where it can erupt and form volcanoes.

Yes, most volcanoes are associated with subduction zones.

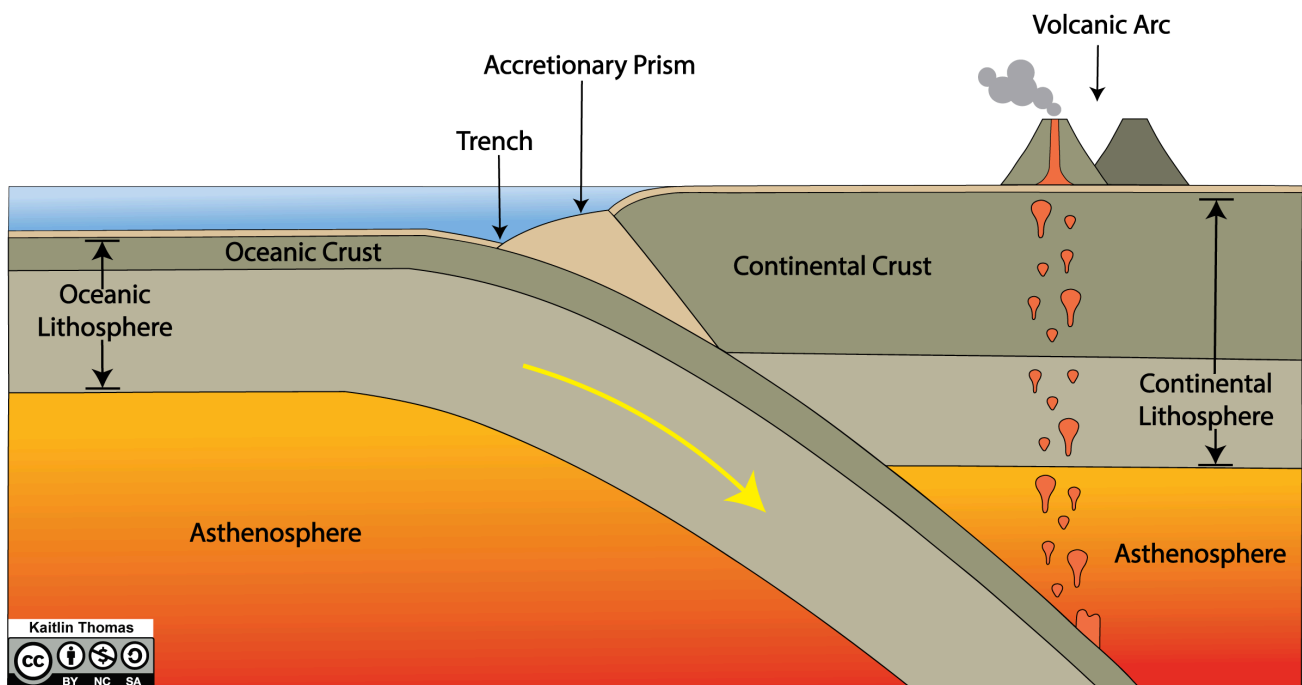


Figure 3.4 – Schematic cross-section showing major features of an ocean-continent subduction zone. Image credit: Kaitlin Thomas, CC BY-NC-SA.

Exercise 3.3 – Connecting Earthquakes and Volcanoes

In the first exercise of this chapter, you discovered the link between the locations of earthquakes, volcanoes, and plate boundaries. Now, let's examine this in more detail. The two maps below show the tectonic settings for Central America and the Western Pacific Ocean; both are subduction zones (Figure 3.5).

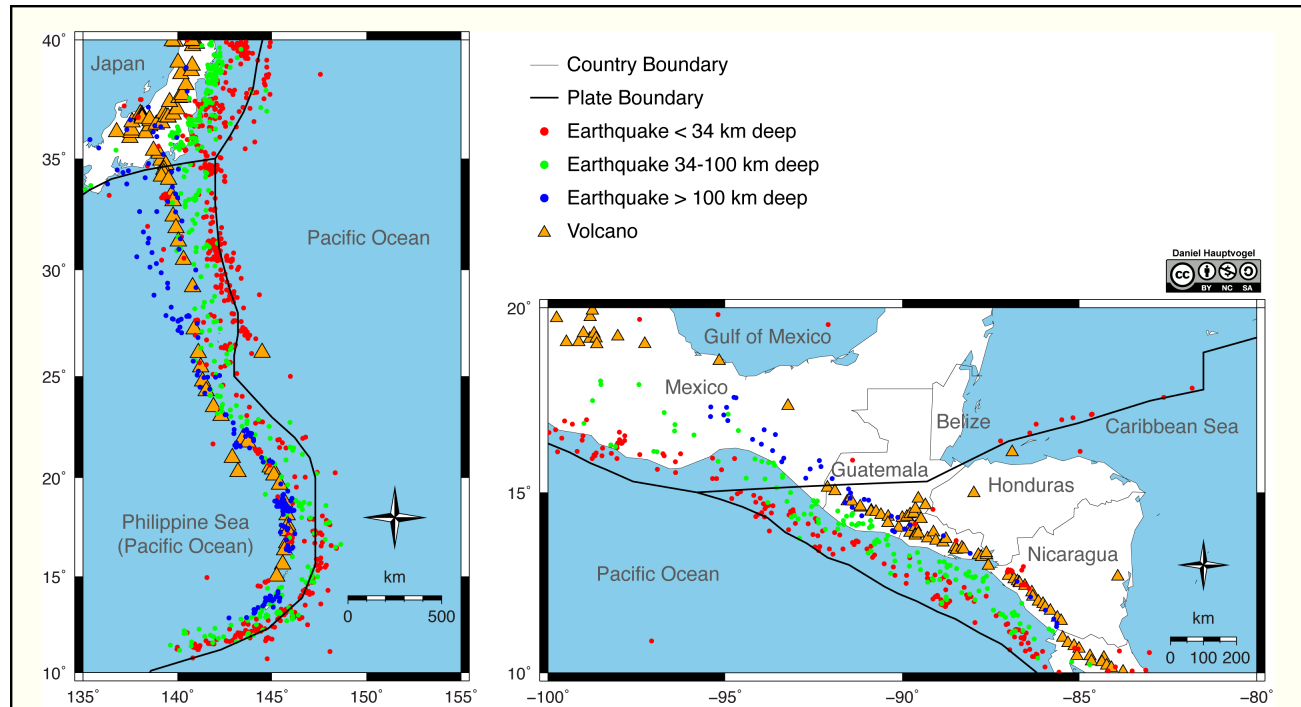


Figure 3.5 – Maps of Central America and the Western Pacific Ocean showing earthquake and volcano locations. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

- a. Look at the maps and describe how the depth of earthquakes changes in a subduction zone. Why does this change occur?

- b. Why are earthquakes common on only one side of a subduction zone?

- c. **Critical Thinking:** What does this information tell you about where earthquakes are most common in subduction zones?

In Exercises 3.1 and 3.2, you may have discovered the link between the locations of volcanoes and plate

boundaries. When you look closely, however, they are not an exact match. In most cases, the volcanoes are some distance from the plate boundary and only located on one side (similar to earthquakes).

- d. Can you find any pattern between the depth of earthquakes and the location of volcanoes? Explain.

- e. Volcanoes are fueled by magma that is produced within the Earth. At what depth do you think magma is produced at subduction zones? Explain.

- f. Based on this information, draw a cross-section of a subduction zone below. Be sure to include the plates involved, earthquake locations, and volcanoes.

Sketch Area:

3.4 Mid-Ocean Ridges, Seafloor Age, and Plate Motion

In WWII, geophysical techniques such as sonar were used to detect submarines and geoscientists realized that this could be used map the seafloor. This led indirectly to the discovery of mid-ocean ridges. Behind the scenes, Marie Tharp almost single handily mapped the sea floor and discovered the Mid-Atlantic ridge. During this same time, Mary Sears headed the Hydrographic Office and mapped sea currents to help predict when naval assaults should occur.

Exercise 3.4 – Investigating Oceanic Lithosphere Age

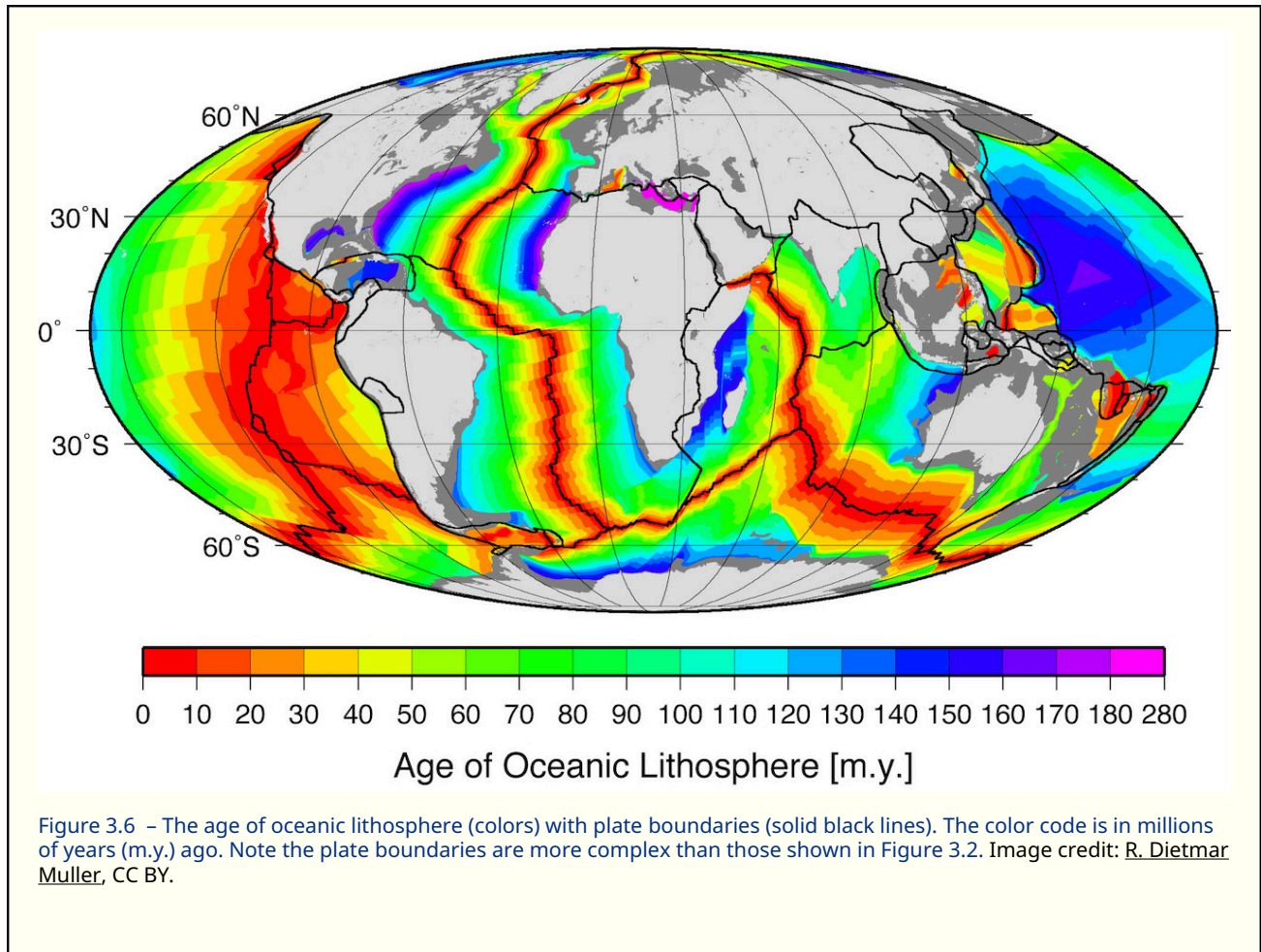
Use the map of oceanic lithosphere age (Figure 3.6) and the plate boundaries map (Figure 3.2) to answer the following questions.

- a. Where is the world's oldest oceanic lithosphere? Describe its tectonic setting.

- b. Where is the world's youngest oceanic lithosphere? Describe its tectonic setting.

- c. Develop a hypothesis that describes what happens to oceanic lithosphere at each of the three types of plate boundaries.

- d. Compare the age of oceanic lithosphere of the Mid-Atlantic Ridge and the East Pacific Rise. Why does the East Pacific Rise have a wider swath of young oceanic lithosphere?



Geodesy, the science of measuring the Earth's shape and positions on it, allows the measurement of plate motion directly using GPS, Global Positioning System. Above us is a network of satellites that is more stable than the Earth's surface, so when a whole continent moves, GPS can detect this movement. Another thing GPS can show is tectonic movements within plates. One assumption behind plate tectonics is that the Earth's lithosphere is rigid. But some say parts of the plates are mobile, like the Tibetan Plateau and the western American mountain belts. GPS data helps separate blocks that move independently, even if only by a few millimeters per year. In the United States, the Sierra Nevada and Baja California micro-plates have been distinguished this way.

Exercise 3.5 – Measuring Plate Motion

Examine the coastlines of eastern South America and western Africa (Figure 3.7). Notice how well they match in shape?

- Select a point along the coasts of each continent that used to be connected together as part of Pangea. Using the scale bar on the bottom right of Figure 3.6, measure the distance between the two points.
 - Distance in kilometers: _____
 - Distance in miles: _____
- This portion of Pangea broke apart about 125,000,000 years ago. Using the distance you measured, cal-

calculate how fast (the rate) South America and Africa are separating. (Rate = Distance/Time; 1 km = 100,000 cm; 1 mi = 63,360 in)

- i. Rate in centimeters/yr: _____
 - ii. Rate in inches/yr: _____
- c. At the current spreading rate, how many years would it take South America and Africa to move apart another kilometer and mile?
- i. Years for 1 kilometer of separation: _____
 - ii. Years for 1 mile of separation: _____



Figure 3.7 – Topographic and bathymetric map of the South Atlantic Ocean, east coast of South America and west coast of Africa. Image credit: Google Earth

This exercise is adapted from [Chloe Branciforte and Emily Haddad](#), CC BY-SA.

3.5 Hotspots

Hotspots are regions where anomalously hot mantle material rises close to the Earth's surface, causing volcanic eruptions (Figure 3.8). When oceanic lithosphere is over a hotspot, volcanic islands will form, like the Hawaiian Islands. When continental lithosphere is over a hotspot, it can create large continental volcanoes, like Yellowstone National Park.

The accepted understanding of hotspots is that they don't move, and the tectonic plates move over the hotspot (Figure 3.8). The part of the tectonic plate over the hotspot is volcanically active because it has

a magma source, and a volcano grows. When that volcano erupts enough material and rises above sea level, a volcanic island forms. As the island moves away from the hotspot due to the movement of the tectonic plate, that volcano is cut off from its magma source and becomes extinct. Weathering and erosion cause the volcano to shrink in size and become submerged in what is called a seamount (basically an underwater mountain). Recently, though, there has been evidence that suggests hotspots are moving as well.

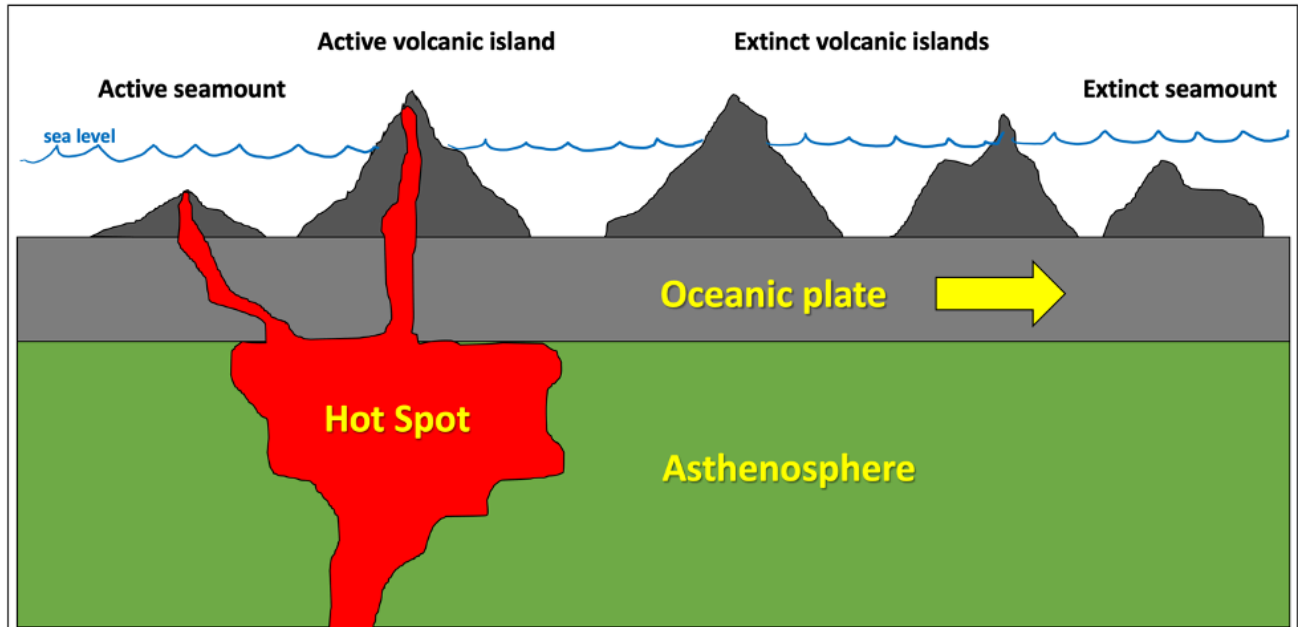


Figure 3.8 – Volcanic evolution over an oceanic hotspot. The hotspot is stationary, and the oceanic plate is moving towards the right. Seamounts are made of volcanic rocks but are still underwater. Image Credit: [Chloe Branciforte](#) and [Cindy Lampe](#) CC-BY.

Exercise 3.6 – Hawaiian Hotspot

In the Hawaiian Islands, only the Big Island of Hawai'i (pronounced Ha-VY-ee in Hawaiian) is volcanically active. The other islands are extinct, but they were active when they were over the hotspot. Use Figure 3.9 to answer the following questions.

- Measure the distance from the big island of Hawai'i to Maui in kilometers and miles. (measure from the center of the islands) _____
- Measure the distance from Maui to Moloka'i. _____
- Measure the distance from Moloka'i to O'ahu. _____
- Measure the distance from O'ahu to Kauai. _____
- Go back to each measurement and determine the rate of movement for each time interval in cm/year (rate = distance/time).
- Has the Pacific Plate moved at a constant rate over the past 5 million years (myr)? Explain your observations.

g. What is the average movement rate of the Pacific Plate over the past 5 myr in cm/year?

h. In what general direction is the Pacific Plate moving? _____

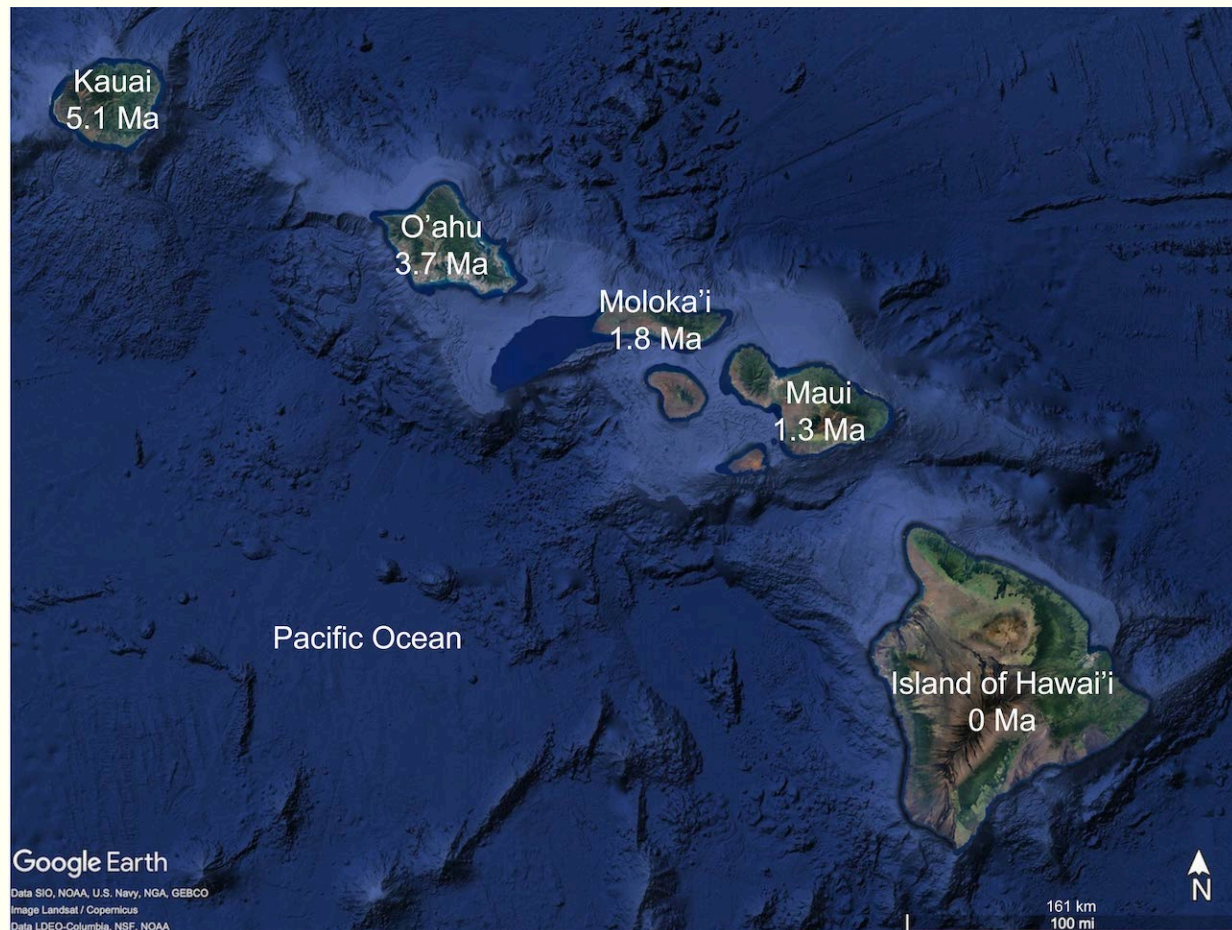


Figure 3.9 – Map of the Hawaiian Islands and their geologic ages. Image credit: adapted from Google Earth.

This exercise is adapted from [Chloe Branciforte and Emily Haddad](#), CC BY-SA.

3.6 Seismic Tomography

Seismic tomography is a modern geophysical technique used to create 2D- or 3D-computer-generated images of the subsurface of the Earth using **seismic waves** from earthquakes and explosions. Seismic tomography plays a crucial role in studying the Earth's **mantle**. Like doctors using CT (computed tomography) scans to study parts of the human body, geoscientists use images produced from seismic tomography to study **core**, mantle, and plate tectonic processes.

Seismic tomography reveals areas of the Earth's interior where seismic waves travel at velocities that are slower or faster than expected. Color variation in cross-sections generated by seismic tomography represents different seismic wave speeds, which can vary within the Earth. One reason why the speed of seismic waves varies is due to temperature differences in different parts of the Earth (Figure 3.10). A typical tomographic color scale shows:

- Warmer colors (red, orange) in areas where seismic waves have traveled slower than expected. These are interpreted as areas with 'hotter' temperatures.
- Cooler colors (blue) in areas where seismic waves have traveled faster than expected. These areas are interpreted as areas with 'cooler' temperatures.

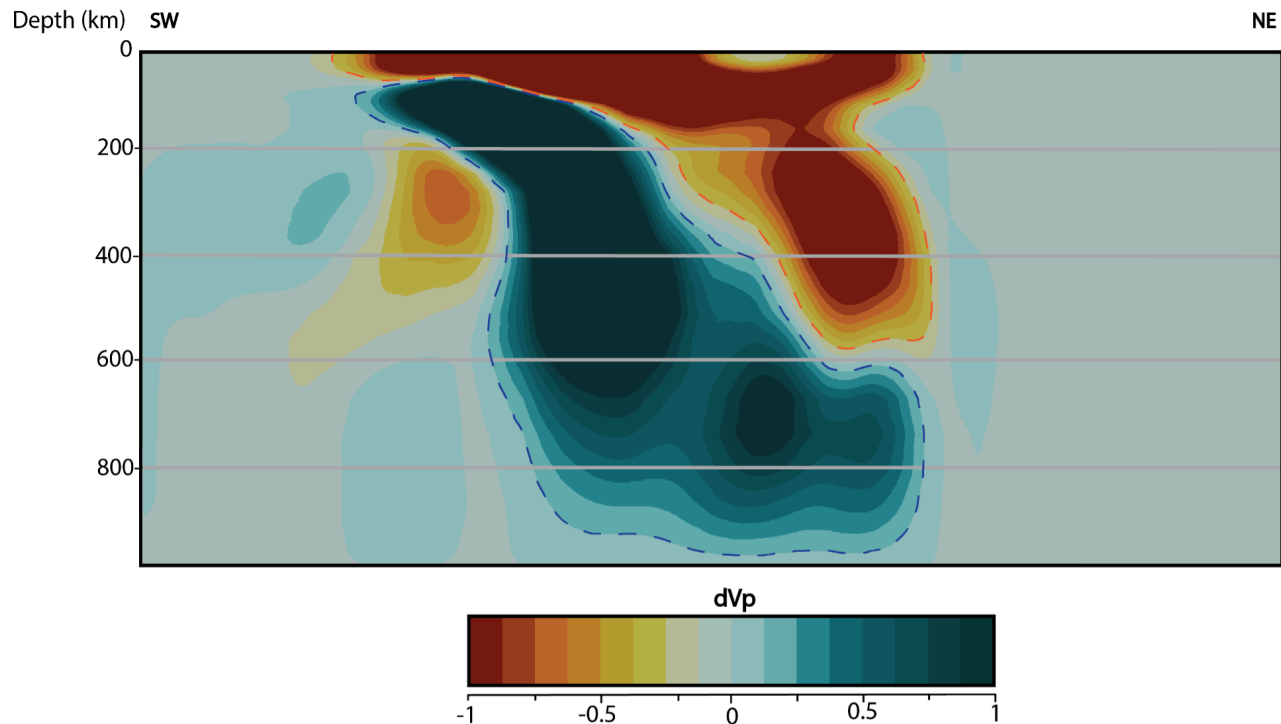


Figure 3.10 – Example of a tomographic cross-section. The cooler-toned area outlined by the dark blue dashed line represents an area of high velocity and cooler temperatures. The warm-toned area outlined by the orange dashed line represents an area of low velocity and warmer temperatures. The color scale at the bottom shows perturbations in the seismic P-wave (primary wave) velocity (dVp). Image Credit: Kaitlin Thomas, CC BY-NC-SA

Exercise 3.7 – Seismic Tomography

In this exercise, you will use [Hades Underworld Explorer](#) to investigate structures in the Earth's mantle.

1. In a web browser, load the [Hades Underworld Explorer](#). **Note: Do not use a Firefox browser.**
2. Navigate to the top right corner of the map window and click on the button titled "Settings (expand)".
3. Check these two boxes: "Show high contrast image" and "Show plate boundaries".
4. Make sure the model is set to "UUP07". This is under the P-Wave Models on the list of tomography models.
5. Utilize both the "Cartesian View" and "Polar View" tabs under the Google Map Explorer to help guide your interpretations.

Part 1:

Line up the "L" and "R" cursors with the locations shown in Figure 3.11 as best as possible. Once you have lined up the cursors, use the "Cartesian View" and the "Polar View" in the area below the Google Map Explorer to answer the following questions.



Figure 3.11 – Map of South America with a green line showing approximate location of the cross-section (thick green line) with ends marked by L (left) and R (right) for Part 1 of this exercise. Also shown are several plate boundaries as thin red, blue, and green lines. Image credit: Screenshot from [Hades Underworld Explorer](#).

- What type of plate boundary is present? _____
- What sort of features can you identify from the tomographic cross-section?

- What is the approximate depth of the blue features in this tomographic cross-section?

- Describe the geometry of the blue features.

- What do the blue features represent? _____
- What is the name of the subducting plate at this boundary? _____

Part 2:

As in the first part, line up the “L” and “R” cursors with the locations shown in Figure 3.12.



Figure 3.12 – Map of the Hawaiian Islands with a green line showing approximate location of the cross-section (thick green line) with ends marked by L (left) and R (right) for Part 3 of this exercise. Image credit: Screenshot from [Hades Underworld Explorer](#).

g. What sort of features can you identify from the tomographic cross-section?

h. How do the velocity and temperature differ in this tomographic cross-section compared to the previous tomographic cross-section?

i. Describe the depth and geometry of the warm features present in this tomographic cross-section.

Additional Information

Exercise Contributions

Daniel Hauptvogel, Michael Comas, Virginia Sisson, Kaitlin Thomas

CHAPTER 4: MINERALS

Classification, Identification, and Critical Minerals

Learning Objectives

The goals of this chapter are to:

- Apply various techniques to determine mineral properties
- Identify common minerals using physical properties
- Analyze critical and strategic minerals

4.1 Geologists Like to Describe and Classify

Geologists must make sense of the Earth's numerous naturally forming materials. Because there are thousands of these materials, a detailed description and classification scheme are important. After all, these Earth materials are where most of the elements used in the manufacturing of everyday items come from.

Exercise 4.1 – Recognizing Earth Materials

To help you learn this classification, use the collection of Earth materials provided by your instructor. Classify and sort these Earth materials into groups based on any criteria you want to use. Your instructor may ask you to re-classify the materials several times using different criteria.

- a. What criteria did you use? Why?

- b. If you were asked to reclassify, what other criteria did you use?

- c. What were the final criteria you used? Do you think this is a better classification scheme than the first one you tried? Why?

An important distinction to make in Earth materials is the difference between a **mineral** and a rock. Minerals are the basic building blocks of rocks, which means rocks are made up of different combinations of minerals or just one mineral in some cases. A mineral is a naturally occurring, usually inorganic, solid that can be defined by a chemical formula and a crystal structure. Figure 4.1a is an example of a rock called granite, which is made up of a combination minerals. Figures 4.1b and 4.1c are two other types of rocks, sandstone and gneiss. They contain the same minerals as the granite in Figure 4.1a. Even though they contain the same minerals, all three of these rocks formed in different ways. We'll get to that a little later, so for now, let's focus on minerals.

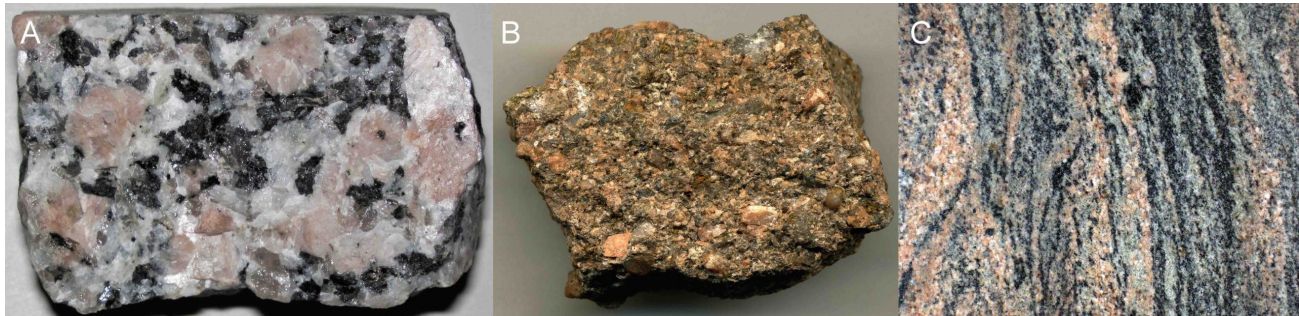


Figure 4.1 – These are three different types of rocks that contain the same minerals: A) granite; B) arkose sandstone; C) gneiss. Pink minerals are K-feldspar, clear minerals are quartz, white minerals are plagioclase feldspar, and black minerals are biotite. Image Credit: James St. John, [A](#), [B](#), and [C](#); all CC BY.

4.2 Physical Properties of Minerals

An essential skill for a geoscientist is to be familiar with mineral names and compositions and be able to recognize them in rocks, but there are over 4,000 known minerals, which makes for an impossible task. Luckily, for most Physical Geology classes, there are only about twenty or so minerals you'll need to be familiar with. The way that you can tell them apart is by their physical properties, which can be observed or tested using common items:

- Color
- Luster
- Streak
- Hardness
- Cleavage and fracture
- Other properties

We will go through these systematically so that you can become skilled at these techniques. Some of the minerals you will work on in this lab are found in many rock types, and others are only found in special settings such as ore deposits.

One more thing: Often, you can find identifying features simply by looking at the mineral. Sometimes, you need to look closer at the mineral using a hand lens (a type of magnifying glass). The correct way to use a hand lens is to hold it up to your eye and move the rock or mineral in or out until it comes into focus (Figure 4.2).



Figure 4.2. A geologist using a hand lens to identify minerals in a rock. Notice that the hand lens is close to her eye. Image credit: [USGS](#) Public Domain.

Color

Color is an eye-catching property of minerals. Some minerals have unique colors, such as **sulfur**, which is always lemon yellow. However, color is not always a diagnostic property because some minerals come in several colors based on the chemical elements present in the crystal structure. For example, **quartz** can come in almost any color, and therefore its color is not diagnostic. Sometimes, the mineral structure is what determines its color. In other cases, a tiny amount of an accessory element will change the color. Also, mineral color can change when exposed to light, heat, or radiation.

Exercise 4.2 – Mineral Color

Even though color is not very diagnostic for most minerals, it's still an important component in narrowing down your mineral identification when combined with other physical properties.

- a. Your instructor has provided you with a selection of minerals. Fill in Table 4.1 with sample numbers for each color.

Table 4.1 – Mineral Color

Color	Mineral Sample Numbers
Black/gray	
Blue	
Green	
Red	
White/clear	
Yellow	
Other: _____	
Other: _____	
Other: _____	

- b. What is the most common color in your assigned minerals? _____
- c. What is the least common color in your assigned minerals? _____
- d. Do you think any of your minerals have a unique color that can be used as a diagnostic property? Explain.

- e. For your minerals that do not have a unique color, is there anything else you can observe to help you tell the difference between them? Explain.

Luster

A mineral's luster refers to how its surface reflects light or its "sheen." Luster can provide valuable infor-

mation when identifying minerals. Generally, a mineral's luster can be described as shiny or dull or, in geologists' lingo – metallic or non-metallic (Figure 4.3). In addition, luster determines how a mineral might be used commercially. The metallic luster of gold and silver makes them attractive, and the pearly luster of muscovite is used in cosmetics. Be careful to observe luster on clean, fresh surfaces as sometimes their luster can change with exposure to **weathering**.

- Minerals with a **metallic luster** look like a polished, highly reflective metal. On a molecular scale, light cannot pass through metallic minerals.
- Minerals with **non-metallic luster** do not look like polished metal. Light does pass through non-metallic minerals. Be careful because these minerals can still be shiny. Many additional terms exist to describe the luster of non-metallic minerals, such as vitreous/glassy, pearly, greasy, dull, earthy, etc., but these aren't the focus of this exercise.



Figure 4.3 – Examples of metallic and non-metallic minerals. Image Credit: Adapted from [Callan Bentley](#), CC BY-NC

Exercise 4.3 – Mineral Luster

Your instructor has provided you with a selection of minerals.

- Identify the luster of your minerals and fill in Table 4.2 with the sample numbers.

Table 4.2 – Mineral Luster

Luster	Mineral Samples
Metallic	
Non-Metallic	

- b. In the lecture, your professor may have described other types of luster than just these two. Do any of your samples have a different type of luster than these?
- c. Did you notice any other differences between your metallic and non-metallic minerals?

Streak

Streak is the color of a mineral's powder. We can observe a mineral's streak by scraping the mineral across a white or black unglazed porcelain plate called a streak plate (Figure 4.4). This may produce a small amount of powder on the surface of the streak plate. Some minerals have a different color streak than the mineral color. Most students use streak in Physical Geology labs but not in other situations.

1. Place a streak plate flat on a table and hold the streak plate firmly.
2. Place part of the unknown mineral on the streak plate.
3. While applying a firm pressure, drag the mineral across the plate.

NOTE: If no powder is created, it means the mineral is harder than the streak plate.

The color of a mineral's streak is often compared to that of the mineral. Figure 4.4 shows how some minerals have the same color streak as the mineral. Notice that two of these have a different streak than that of the mineral.



Figure 4.4 – Four different dark gray metallic minerals with varying streak colors. The minerals are from the upper left clockwise: hematite (red-brown), magnetite (black), sphalerite (honey-brown), and galena (dark gray). Image credit: [Karla Panchuck](#), CC BY.

Exercise 4.4 – Mineral Streak

Your instructor has provided you with a selection of minerals.

- a. Identify the luster of your minerals and fill in Table 4.3 with your sample numbers.

Table 4.3 – Streak Color

Streak Color	Mineral Sample Numbers
Same as mineral color	
Different than mineral color	
Did not produce a streak	

- b. Do you notice anything common between minerals whose streak color differs from the hand sample color? Explain.

- c. **Critical Thinking:** Do you think it would be useful to carry a streak plate with you when going to look at minerals in the field? Why or why not?

Hardness

The hardness of a mineral is a measure of its resistance to scratching. The Mohs Hardness Scale ranks the relative hardness of minerals from 1 to 10, with 1 being the softest and 10 being the hardest (Figure 4.5). Mohs scale is qualitative, which means there is no quantitative relationship between hardness values. This is one of the most important diagnostic properties for identifying a mineral. It is, however, one of the hardest to do in a rock because it has small mineral grains.

A mineral's hardness is determined by a scratch test using materials of known hardness. The idea is that harder substances will be able to scratch softer ones. Common materials such as fingernails, copper coins such as pennies, glass, steel nails, and porcelain plates are used to conduct scratch tests, and all vary in hardness. To conduct a scratch test:

1. Try to find a corner of the mineral that has not been too scratched up.
2. Scratch the mineral. It is best to start with a utensil that is lower on the hardness scale and "work your way up" the scale by using harder utensils. If the mineral seems similar to the thing you're

using to scratch – scratch it really hard. When using the glass, try scratching the glass with the mineral, don't try to scratch the mineral with the glass.

3. When you scratch a mineral, sometimes it's hard to tell if the powder is coming from the mineral (if you scratched the mineral), or if it's coming from the thing you used to scratch it (the mineral is harder than the utensil). In this case, wipe the surface of the mineral with your finger to see if there is an actual mark left. If there is a mark, the utensil scratched the mineral.

Mohs Hardness Scale		
Mineral Name	Mohs Number	Common Object
 → Diamond	10	
→ Corundum	9	←  Masonry Drill Bit (8.5-9)
→ Topaz	8	
→ Quartz	7	←  Steel Nail (6.5)
→ Orthoclase	6	←  Knife/Glass Plate (5.5)
→ Apatite	5	
→ Fluorite	4	←  Copper Penny (3.5)
→ Calcite	3	←  Fingernail (2.5)
→ Gypsum	2	
→ Talc	1	

Virginia Sisson
CC BY-NC-SA

Figure 4.5 – This is the Mohs scale of relative mineral hardness that uses 10 minerals with no quantitative relationship between the values. Lower numbers mean softer minerals; higher numbers mean harder minerals. On the right side is a list of common objects and their Mohs hardness used to test unknown minerals. Note: Manufacturing differences can make the hardness of these common objects vary slightly. Image credit: Virginia Sisson, CC BY-NC-SA.

Exercise 4.5 – Mineral Hardness

Your instructor has provided you with a selection of minerals.

- a. Determine the hardness of each of your minerals and fill in the sample numbers for each hardness in Table 4.4.

Table 4.4 – Mineral Hardness

Hardness	Mineral Sample Numbers
< 2.5	
2.5 – 3.5	
3.5 – 5.5	
5.5 – 6.5	
> 6.5	

b. What is the most common hardness value? Why?

Cleavage and Fracture

Cleavage is a term used to describe how minerals can break in a predictable way. When minerals break along planes in which chemical bonds are weak, they produce flat surfaces called cleavage planes. Minerals can have 1, 2, 3, or more planes of cleavage (Figure 4.6). When there is more than one plane, the angle between the planes needs to be described. Cleavage is one of the most challenging concepts for introductory geology students, but it is a useful property for identifying minerals. For example, amphibole and pyroxene have the same physical properties except for cleavage. Knowing whether a rock contains amphibole or pyroxene could reveal a lot about that rock's geologic history, such as where and how it most likely formed.

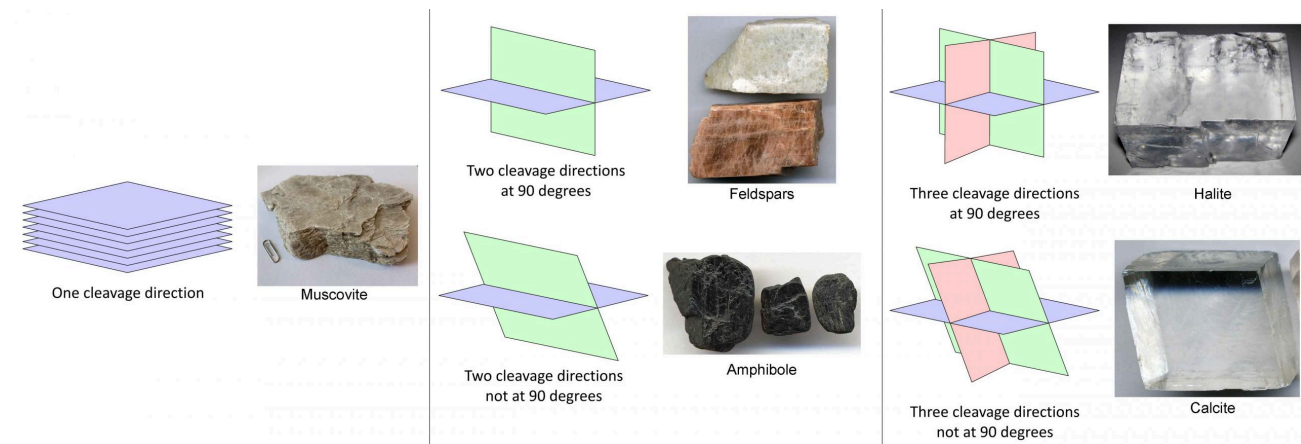


Figure 4.6 – Types of cleavage with mineral examples. Cleavage differs by the number and angle between cleavage planes. Image credit: cleavage models adapted from [M.C. Rygel](#); muscovite from Daniel Hauptvogel, all other minerals from [James St. John](#), CC BY-SA.

While the concept of mineral cleavage is difficult, identifying cleavage in minerals doesn't have to be. When looking at a mineral, the easiest way to identify cleavage is to shine a light on its surface. If that surface brilliantly reflects light, then you most likely have a cleavage plane. Today, just about everyone has a cell phone with a flashlight that can be used to identify cleavage. Or you can move the mineral around underneath an overhead light or use sunlight.

Minerals don't always break in predictable ways, and that's when we use the term fracture. Fracture describes irregular breakage in minerals, which usually occurs on mineral planes that don't have any weak bonds (Figure 4.7). This sounds easy enough; flat surfaces mean cleavage and uneven surfaces mean fracture, but the truth is that it can be messy. Minerals can appear to have flat surfaces that are not actually cleavage, and fracturing can occur along planes of cleavage. This is why you need to look closely at the surface of a mineral using a hand lens.

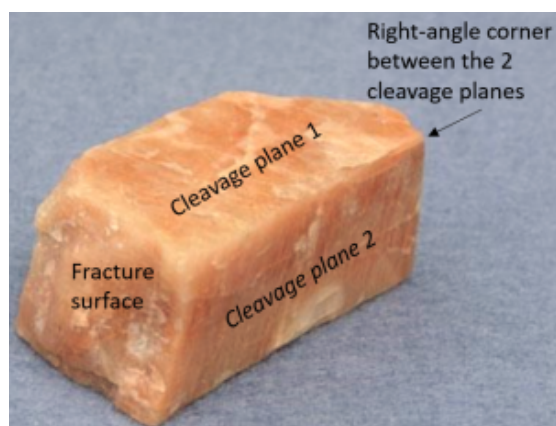


Figure 4.7 – Potassium feldspar displaying two planes of cleavage and one irregular fracture surface. Image credit: [Steven Earle](#), CC BY.

You may need to use a hand lens to see a mineral's cleavage. To use the hand lens properly, you need to place the lens up against your face and then move the mineral or rock sample back and forth to get it into focus. A common mistake students make is holding the mineral or rock at arm's length and moving the hand lens; this is incorrect and will not help you see small-scale features in rocks and minerals.

Another thing that makes identifying cleavage difficult is the entire mineral sample does not have to take

on the shape of the cleavages. Instead, you need to use a hand lens to look at the small details of a single side of the mineral. There will be slight changes in the heights of the surface that you wouldn't be able to see without the hand lens. It is along those "elevation" changes that you should be looking for signs of cleavage. Then repeat your examination on the other sides.

This is probably the most difficult property to learn. For some minerals, it is also the most diagnostic property to distinguish them from similar-looking minerals.

Exercise 4.6 – Mineral Cleavage

Your instructor has provided you with a selection of minerals.

- Determine the number of cleavage planes and angles between them for each of your minerals and fill these numbers in on Table 4.5.

Table 4.5 – Mineral Cleavage

Cleavage	Mineral Sample Numbers
1 plane	
2 planes at 90°	
2 planes not at 90°	
3 planes at 90°	
3 planes not at 90°	
No cleavage fracture only	

- Do all minerals have cleavage? Why or why not?

- Since cleavage can be used to distinguish between two minerals, give the sample number of two minerals that look similar but have different cleavage. What are the similar properties for these two minerals?

- d. Does a lack of cleavage help you distinguish between two similar looking minerals? If so, which minerals are these?

- e. Sometimes, instead of using cleavage planes, you can distinguish a mineral by the pattern developed when a mineral is broken. Do any of the samples that lack cleavage have a distinctive fracture pattern. Describe it.

Other Properties

Minerals can also have other diagnostic properties. For many minerals, these are unique and an easy way to identify the mineral. Properties that might be useful include:

- **Magnetism** – Some minerals may be magnetic and are attracted to magnets. This property can help identify certain minerals, such as magnetite. Hematite is also weakly magnetic.
- **Reactivity** – Certain minerals may react with acids and fizz or effervesce. For example, calcite will react with weak hydrochloric acid and fizz. Geologists use acid that is about the same strength as vinegar for mineral testing. Be sure to wipe up any spills and don't get the acid on your clothes.
- **Taste, Touch, and Odor** – Some minerals have distinct tastes (ex. halite tastes salty), feels (ex. talc feels greasy), or odors (ex. sulfur smells like rotten eggs) that can aid in identifying minerals.
- **Optical Properties** – Some minerals may exhibit optical properties, which can be useful for mineral identification. Try looking at printed text through a calcite crystal, and you may see a "double image." This optical property is called double refraction and is caused by light splitting into two rays with different velocities and directions of propagation.
- **Density** – Density is the mass per unit volume of a mineral. Different minerals have different densities due to varying chemical compositions. You can get a general understanding of a mineral's density by feeling the weight of the mineral in your hand. A dense mineral may feel particularly heavy. Galena is an example of a mineral with a high density.
- **Fluorescence** – One of the most amazing properties seen by shining a UV light source at a mineral. Calcite and gypsum often fluoresce. Be careful not to shine UV light into anyone's eyes as it can damage the eye.
- **Twinning** – One property that you probably haven't thought about is how minerals interact when the crystals are growing. Some minerals grow together resulting in two or more intergrown crystals that are mirror images of each other. This symmetry is called twinning. Staurolite crystals can grow together and form a distinctive cross that is a result of twinning.

Exercise 4.7 – Other Mineral Properties

Your instructor has provided you with a selection of minerals.

- a. Determine which of your minerals exhibits any other properties and record them in Table 4.6.

Table 4.6 – Other Mineral Properties

Property	Mineral Sample Numbers

- b. Which is your favorite unique property from this list? Why?

4.3 Mineral Names

Nowadays, mineral names are based on mineral appearance, mineral chemistry, where the mineral is found, a famous scientist, or anything else deemed important by a mineral's discoverer. The naming of minerals has changed over time from alchemistic beginnings to the advanced science of today. You will notice that many mineral and rock names end in *ite*." The suffix "ite" is derived from the Greek word *ites*, the adjectival form of *lithos*, which means rock or stone.

In antiquity, distinctive physical characteristics, such as color, were used for a mineral's name. For example, garnet comes from an old French word *grenate* for blood-red. Two minerals with similar composition are malachite and azurite (both $\text{Cu}_2\text{CO}_3(\text{OH})_2$). Malachite comes from the Greek word *malakee* or *malache*, used to describe the green leaves of the mallow bush. Azurite comes from *azure*, the Arabic word for blue. Another blue mineral is kyanite which comes from *kyanos*, the Greek word for blue. Some minerals have been named for their chemistry or their structure. For example, cavansite is named for its chemistry (**calcium vanadium silicate**), and pentagonite is named after a five-sided pentagon is five-sided.

So, if you suspect you have a new mineral, your proposed name gets approved by the Commission on New Minerals, Nomenclature and Classification part of International Mineralogical Association (IMA). Also as of July 2023, the Handbook of Mineralogy lists 5,663 species, and the IMA Database of Mineral Properties/Rruff Project lists 5,956 valid species (IMA/CNMNC) of a total of 6,189 minerals. Fortunately for you,

there are just about a dozen mineral names that you should learn to recognize. See the appendix for the origin of the common mineral names.

Exercise 4.8 – Name Your Minerals

Use the information you gathered in Tables 4.1 to 4.6 to identify the minerals and complete the ID table. Your instructor will provide you with an identification table of common minerals and their physical properties. Based on the properties you observed for your unknown minerals, determine their names. Record the names in the identification table.

- Are any of your minerals identifiable using only one of these properties? List the mineral names and the property.

4.4 Critical and Strategic Minerals

If we already know so much about minerals, why do we keep on studying them. The simple answer is they are often resources used to make our lives better. For example, over the past 20 years, annual trade in energy-related critical minerals has increased from US\$ 53 billion to US\$ 378 billion. Critical and strategic minerals play a significant role in national security, the economy, renewable energy development, and infrastructure. The list of minerals the United States has deemed critical and their uses can be found on the [USGS website](#). You'll notice that most of the names on this list are just elements, like aluminum or lithium. Many elements on the periodic table do not occur freely in nature. Naturally occurring deposits of pure aluminum or lithium do not exist on Earth. Instead, these elements are included as part of the chemical composition of minerals, and these minerals need to be mined and processed to extract the elements. For example:

- Aluminum primarily comes from a type of rock called bauxite, which contains minerals such as [gibbsite](#) [$\text{Al}(\text{OH})_3$], [boehmite](#) [$\gamma\text{-AlO}(\text{OH})$], and [diaspore](#) [$\alpha\text{-AlO}(\text{OH})$].
- Lithium primarily comes from the minerals [petalite](#) [$\text{LiAlSi}_4\text{O}_{10}$], [lepidolite](#) [$\text{K}(\text{Li},\text{Al})_3(\text{Al},\text{Si},\text{Rb})_4\text{O}_{10}(\text{F},\text{OH})_2$], and [spodumene](#) [$\text{LiAl}(\text{SiO}_3)_2$] as well as [brines](#) (salty water that contains a lot of dissolved elements or compounds).

Exercise 4.9 – Critical and Strategic Minerals of the U.S.

While the U.S. has its own sources of some critical minerals, it's still reliant on imports to meet manufacturing needs.

- Figure 4.8 shows the known locations of critical minerals in the United States. What are some of the most common critical minerals?

a. What are some of the least common critical minerals?

b. Geologically speaking, where are most of the critical mineral deposits found?

c. Are any of the minerals in your kits considered critical or strategic? _____

d. Which critical minerals are found in your state? (Not from the U.S.? Look at this [interactive world map](#) for your country instead.)

e. Despite having significant critical mineral deposits, the United States is still heavily dependent on importing critical minerals (Figure 4.9). Which two countries is the U.S. most dependent on for critical minerals? _____

f. Let's visualize where the United States imports critical minerals from. Complete the pie graph using data from Figure 4.10 for the number of critical minerals imported per country.

g. **Critical Thinking:** Gallium is an example of a critical mineral found in many areas of the U.S. but has not been produced since 1987, according to the [USGS](#). Why do you think the U.S. isn't producing gallium?

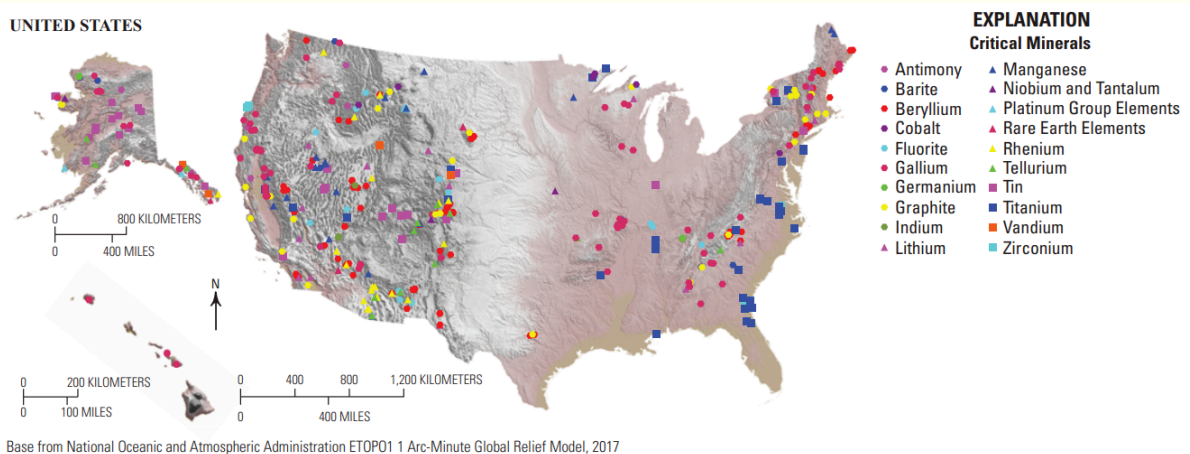


Figure 4.8 – Known critical mineral sources in the United States. Image Credit: [USGS](#), Public Domain, 2022.

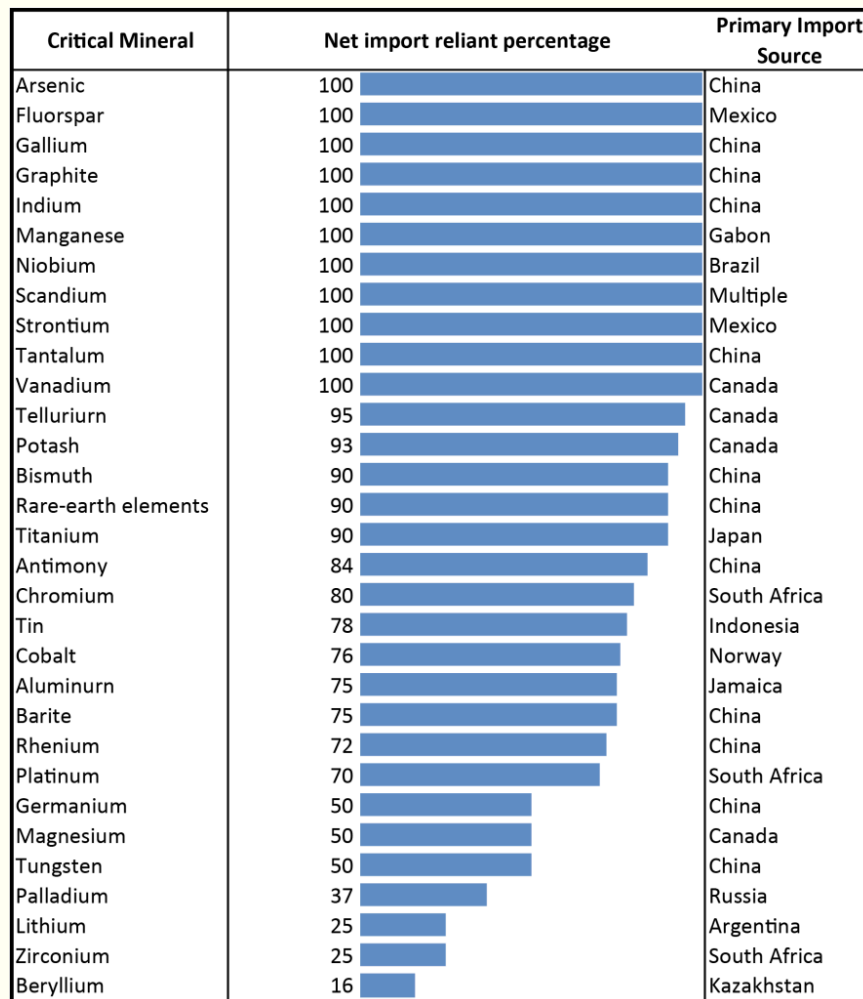
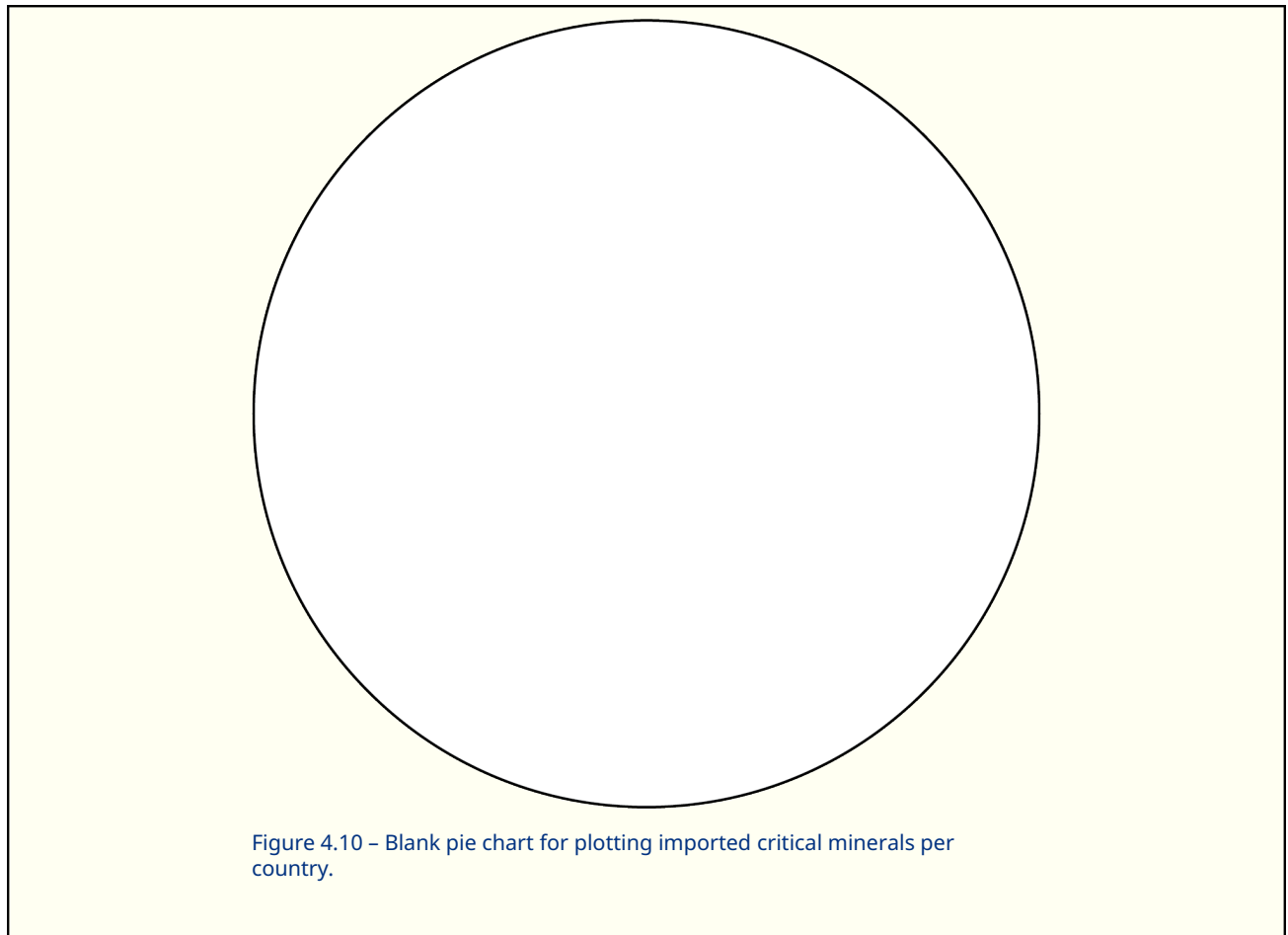


Figure 4.9 – Critical minerals imports for the United States from 2017-2020. Values reflect the reliance on imports as a percentage of consumption. For example, 37% of the palladium consumed in the U.S. was imported. The primary import source is the largest supplier of that mineral to the U.S. (not necessarily the only supplier). Helium is excluded because the U.S. is a net exporter, and Scandium data is excluded because the data is not complete. Data from the [USGS](#), 2022, Public Domain. Image Credit: Daniel Hauptvogel CC-BY-SA 4.0.



Additional Information

Exercise Contributions

Virginia Sisson, Daniel Hauptvogel

CHAPTER 5: THE ROCK CYCLE

Three Types and Their Distribution

Learning Objectives

The goals of this chapter are to:

- Recognize three rock types and how they form
- Compare and contrast rock types
- Evaluate the distribution of rock types in North America

5.1 The Rock Cycle

Rocks are solid materials that are primarily made up of minerals. Most of the time, rocks are a combination of minerals that are held together, and sometimes rocks can be made up of just one mineral (not a single mineral crystal, but many crystals of the same type held together). There are three rock types:

- Igneous rocks form when magma or lava cools and solidifies
- Sedimentary rocks form when pieces of weathered and eroded rocks are cemented together, or when minerals precipitate from a solution
- Metamorphic rocks form when pre-existing rocks are altered by heat and pressure.

Plate tectonics and other natural processes slowly change rocks from one type to another. The **rock cycle** (Figure 5.1) is the traditional way geologists have shown the relationships between rock types, including the processes that tie them together. These processes result in distinctive textures, a term geologists use to describe the size, shape, and arrangement (or fabric) of mineral grains in rocks. Broadly speaking, igneous and metamorphic rocks have a crystalline texture, meaning the minerals are interlocking and intertwined with each other. In igneous rocks, the mineral grains are randomly oriented, but in most metamorphic rocks, the mineral grains have a preferred orientation. Sedimentary rocks mainly have a clastic texture, where mineral grains are separated by cement.

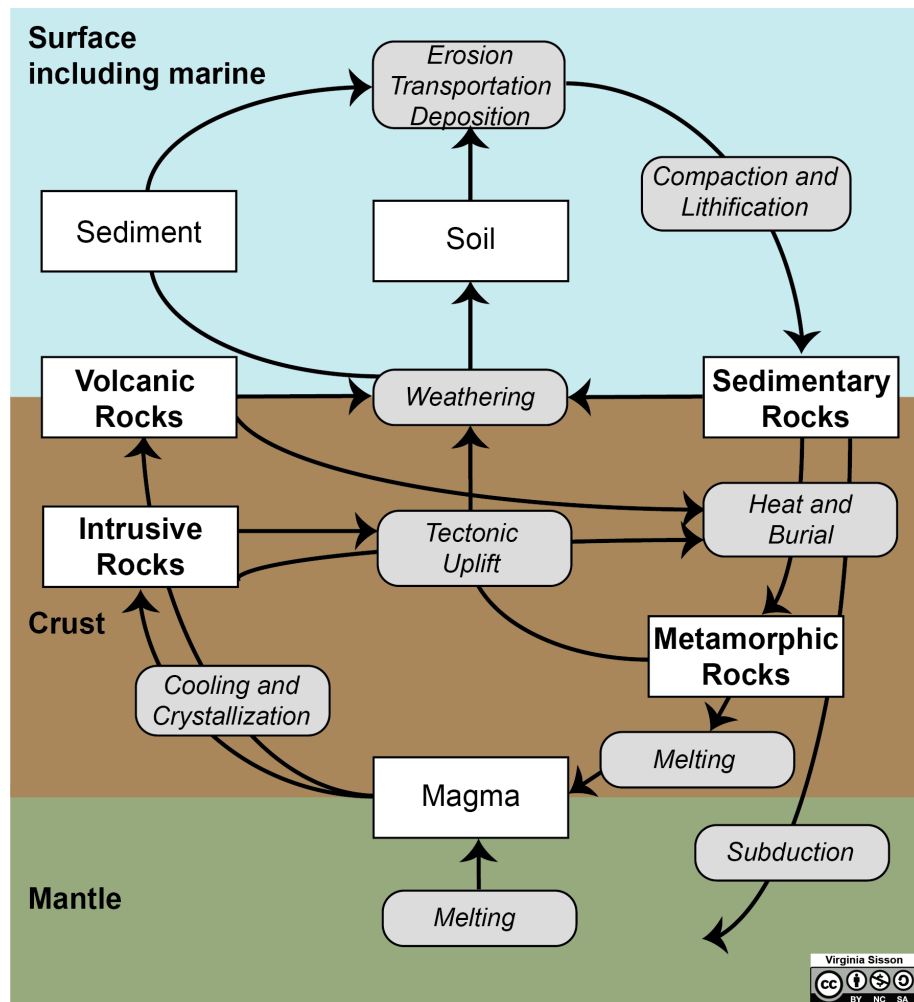


Figure 5.1 – Rock cycle showing igneous, sedimentary and metamorphic rocks. Gray boxes indicate various geologic processes that link these rocks. Bold print for the types of rocks. Image credit: Virginia Sisson, CC BY-NC-SA.

Exercise 5.1 – Recognizing Rock Textures

Your instructor has given you three different rocks.

- Create a sketch of each rock in Table 5.1. Sketches should take no more than 1 minute and capture the essential features.

Table 5.1 – Sketching textures

Rock 1 Sketch:	Rock 2 Sketch:	Rock 3 Sketch:
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- b. Are there any similarities between these rocks? Describe them.

- c. Are there any differences between these rocks? Describe them.

5.2 Rock Formation

Igneous rocks form as magma or lava (molten rock) cools off and solidifies. As the magma cools, minerals crystallize, growing intertwined with each other and forming an interlocking, or crystalline, texture. If the magma cools slowly within the Earth, mineral crystals can grow fairly large (you can see them without magnification), forming an intrusive igneous rock. If magma erupts onto the surface, it's called lava. Since lava is at Earth's surface, it cools rapidly and mineral crystals cannot grow very large (you would need magnification to see most of the minerals), or minerals may not even grow at all.

When rocks are exposed at the surface they begin to break apart physically and chemically through weathering processes. These particles that break off are called sediment. Weathering can also produce soil (sediment with organic matter). Sediment is transported and deposited by wind, water, or ice. As sediment accumulates, those at the bottom are compressed and water is squeezed out of the pore spaces. During this process, new minerals can precipitate in the pore spaces that act as a cement to hold the grains of sediment together, giving us sedimentary rocks. Sedimentary rocks can also form when minerals precipitate out of a solution and undergo the same processes.

Metamorphic rocks form when pre-existing rocks are changed by heat and pressure. Through tectonic processes, igneous, sedimentary, and even other metamorphic rocks can be buried deep within Earth's crust where temperature and pressure is much higher. As these rocks are heated up and squeezed, minerals undergo physical and chemical changes to create metamorphic rocks. If this process continues, these rocks may start to melt which starts the cycle over again with igneous rocks.

Exercise 5.2 – Understanding Rock Formation and Textures

In this exercise, you will learn how rocks form using analogues. Your instructor will provide demonstrations and ask you to make observations and/or sketches.

These experiments are based on those by Allan Ludman and Stephen Marshak in *Laboratory Manual for Introductory Geology*.

You can also do two open-access alternatives that use [chocolate](#) and [crayons](#) to demonstrate how rocks form.

Over the next several lab classes, you'll be asked to identify rocks. The first step to identify a rock is to categorize the rock into one of the three main types or groups of rocks. Igneous, sedimentary and metamorphic rock types are distinguished by the processes which form them. Some of the observations you need to make are similar to minerals, such as color, but others such as cleavage and hardness only apply to minerals within rocks. For many rocks, texture is what distinguishes them from other types of rocks.

Exercise 5.3 – Determining Rock Types

Your instructor has given you a set of rocks. Using your knowledge of how rocks form and their textures, classify your rocks as igneous, sedimentary, or metamorphic. Fill in Table 5.2.

Table 5.2 – Rock type identification

Igneous Rock Samples	Sedimentary Rock Samples	Metamorphic Rock Samples

5.3 Why Study Rocks?

Why should you study different types of rocks? Well, they all contain clues about what the Earth was like in the past. Perhaps one area may have sedimentary rocks which experienced an environmental change from a desert to a swamp to a coral reef under the sea. Different rocks form under only certain conditions, and even the dullest gray rock can tell us something important about the past. Some types of things that rocks can tell us about our planet as well as other planets are:

- Was there a lake or a volcano present where the rock was found?
- Was there a mountain range or a sea?
- Was it hot or cold?
- Was the atmosphere thick or thin?

For example, by understanding where volcanos have occurred in the past, we have a much better idea of

where they are likely to occur in the future and can be prepared for them. Second, by gaining an understanding of how planets work, we can better predict how the Earth will react to changes. If we understand how the Earth and its life responded to temperature changes in the past, we might better understand the effects of the global warming that is happening today.

So the basic point is to better understand our world. This helps us to better coexist with nature and reap the benefits that it has to offer.

Exercise 5.4 – Rock Types in North America

Look at the distribution of rock types at the surface in North America (Figure 5.2) and answer the following questions. Remember that these maps show you rocks at the surface of the Earth.

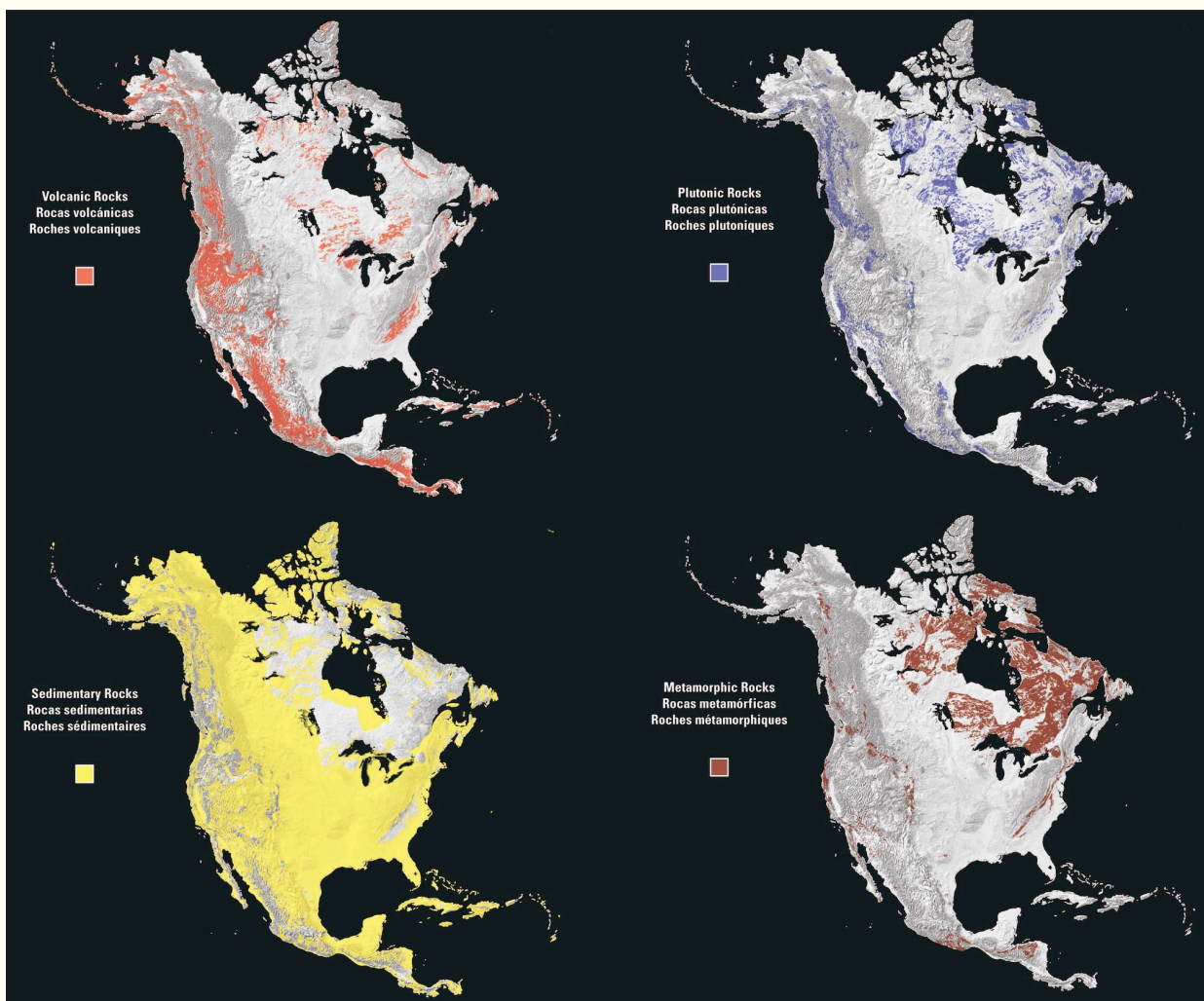


Figure 5.2 – Distribution of rock types at the surface in North America. Note that igneous rocks are shown as both volcanic (extrusive) and plutonic (intrusive) rocks. Image credit: adapted from the [USGS](#), Public Domain.

- What is the most abundant rock type in North America? _____
- Describe the distribution of each rock type. For example, do you see any patterns or are those rocks only located in certain areas?

- c. **Critical Thinking:** These maps only show what is exposed is at the surface. Why does one rock type cover most of North America?

- d. **Critical Thinking:** Cratons are the nuclei of continental plates composed of intrusive igneous and metamorphic rocks. Where do you think the craton of North America is located? What is your reasoning?

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson

CHAPTER 6: IGNEOUS ROCKS

Classification, Mapping, and Volcanic Hazards

Learning Objectives

The goals of this chapter are to:

- Characterize and classify igneous rocks
- Analyze volcanic frequency and hazards
- Determine volcanic stratigraphic relationships

6.1 Igneous Rocks and Earth's Layers

The upper layers (mantle and crust) of the Earth are mainly composed of igneous rocks, although sedimentary rocks are the most abundant on the surface. You probably have learned that these layers formed early in its history through the process of chemical differentiation, when denser elements sank towards the center of the Earth and less dense elements floated toward the surface. This led to density differences between the layers as well as chemical differences.

Exercise 6.1 – Determining the Density of Earth's Layers

Your instructor has presented you with three examples of Earth's layers: oceanic crust, continental crust, and the upper mantle.

- a. Describe the differences between the three rocks.

- b. Measure the density of each sample as you did at the end of Chapter 1. Weigh each sample and record the mass, then record how much water is displaced when you place it in a graduated cylinder. Fill out table 6.1.

Table 6.1 – Density calculation

Rock	Mass (g)	Volume (cm ³)	Density (g/cm ³)

c. How do your measured densities compare with your observations in *a*?

d. What do you think causes the varying densities of these rocks?

e. On Figure 6.1, show where these rocks could come from.

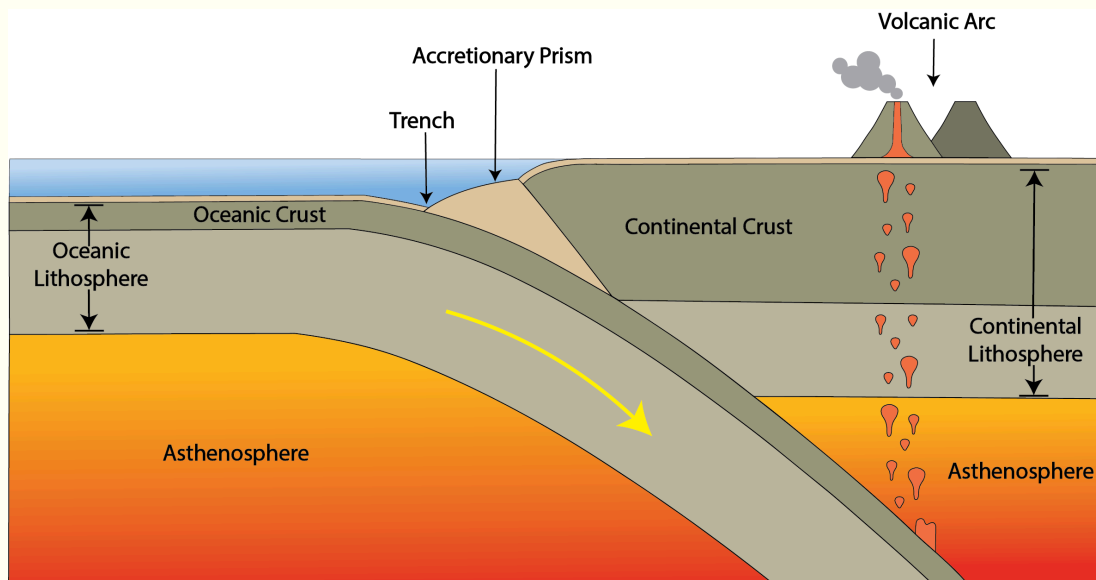


Figure 6.1 Schematic cross-section of an ocean-continent convergent zone. Subduction direction of oceanic crust is shown by yellow arrow. Not to scale as vertical scale is exaggerated. Sedimentary rocks shown in tan, crust in dark gray, lithosphere in light gray with asthenosphere in shades of orange. Image credit: Kaitlin Thomas, CC BY-NC-SA.

6.2 Classifying Igneous Rocks

The classification of igneous rocks is based on chemistry and **texture**, which means it's based on the min-

erals present and how large the mineral grains are (Figures 6.2 to 6.5). The magma's chemistry and temperature determine which minerals will form. There are eight common minerals in igneous rocks (Figure 6.2), which can be separated into four different igneous compositions: **ultramafic**, **mafic**, **intermediate**, and **felsic**.

The size of the mineral grains is chiefly determined by how quickly the magma cools. Slow cooling rates (thousands to half a million years) make larger mineral grains, creating intrusive (plutonic) igneous rocks. Fast cooling rates (instantaneous to hundreds of years) produce smaller grains, creating extrusive (volcanic) igneous rocks. The distinction between fine and coarse grains is whether you can identify the minerals without magnification. This is important because two different rocks can have the same composition, but different textures (small grains vs. large grains). For example, diorite (large grains, intrusive igneous rock) and andesite (small grains, extrusive igneous rock) have the same minerals but different textures.

The common textures of igneous rocks are:

- **Coarse** (phaneritic) – grains are large enough to identify without magnification, indicative of slow cooling; intrusive rocks
- **Fine** (aphanitic) – grains are too small to identify without magnification, indicative of fast cooling; extrusive rocks
- **Porphyritic** – grains are a mixture of coarse and fine grains, indicative of two cooling rates, slow at first (intrusive) and then fast (extrusive)
- **Glassy** – very smooth texture with no minerals, cooled so quickly that minerals did not have time to form, commonly has conchoidal fracture; extrusive rocks
- **Vesicular** – rough, porous texture, cooled quickly, vesicles (holes) created from abundant gas in the lava; extrusive rocks

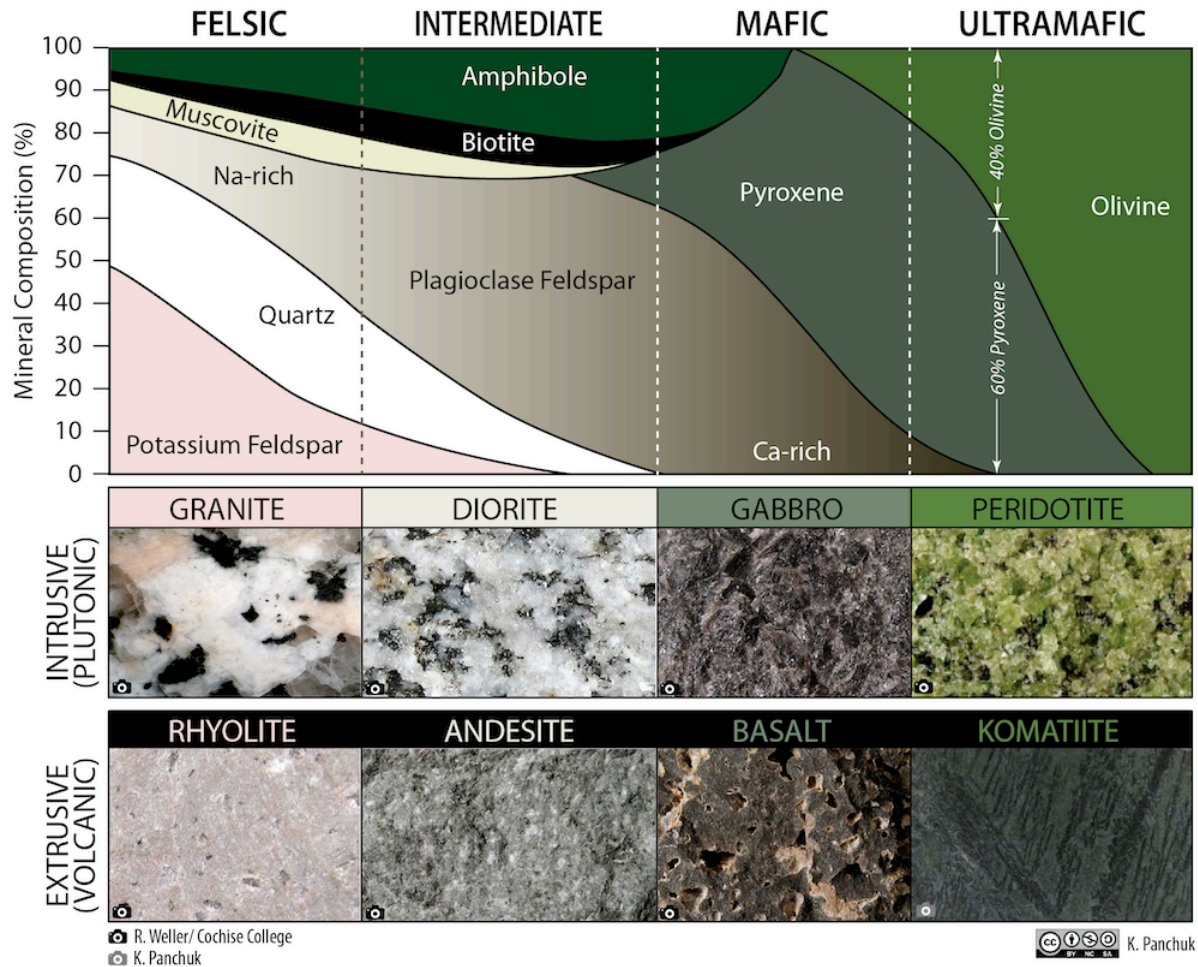


Figure 6.2 – Classification chart of igneous rocks based on the mineral content. The top part is a graphical comparison of silica content and mineral content for extrusive and igneous rocks. To use this graph, determine the relative abundance of seven common minerals in igneous rocks. The bottom two rows compare rocks with the same mineral composition but different names based on whether they formed intrusively or extrusively. Image credit: [Karla Panchuk](#) after Steven Earle, CC BY-SA-NC.

How would you identify minerals in an extrusive igneous rock if the grains are too small to see? There are a couple of tricks that geologists use to identify which type of igneous rock they have. Do you remember how color was not a diagnostic property for minerals? Well, color in an igneous rock can be diagnostic! Iron and magnesium-bearing minerals are either black or green in color, like olivine and pyroxene, and they are the primary minerals that make up mafic and ultramafic igneous rocks. Potassium, aluminum, and silica-rich minerals, like quartz and potassium feldspar, are lighter in color and make up intermediate and felsic igneous rocks. Geologists can use the color of igneous rocks and the relative amount of light- vs. dark-colored minerals to help identify them (Figures 6.2 and 6.3).

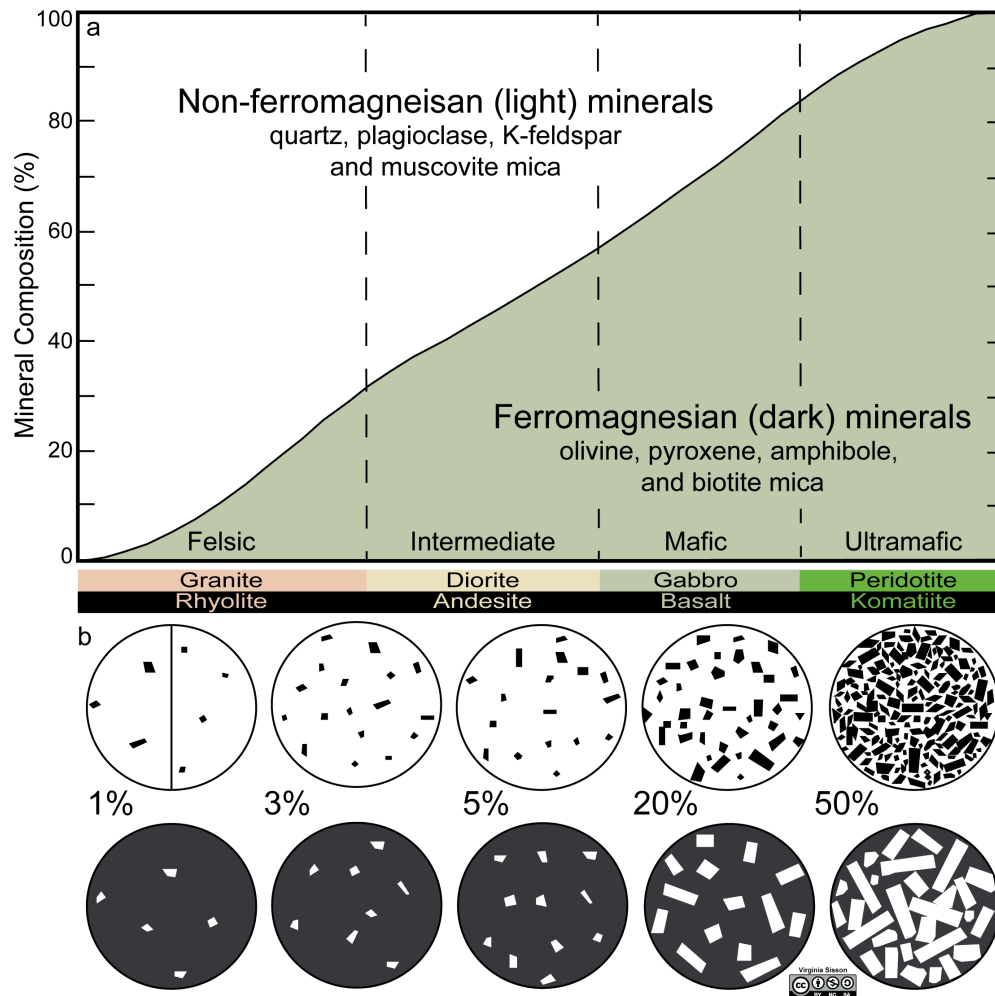


Figure 6.3 – Identifying igneous rocks using mineral color. a) The relative percentages of light (felsic) and dark-colored (mafic – iron and magnesium-rich) minerals, b) Images you can use to estimate percentages of light- and dark-colored minerals. Note: our eyes tend to overestimate the amount of dark colors, so be careful when looking at the rocks. Also, for low abundances of accessory minerals, their size will influence your results. Image credit: Virginia Sisson, CC BY-NC-SA.

Glassy and vesicular textures are a little different (Figure 6.4). These rocks form when lava cools off too quickly for minerals to form. The **conchoidal** fracture in obsidian tells us that it has a high silica content (felsic) despite its dark color. The dark color comes from the tiny amount of iron present.

Photos: R. Weller/Cochise College

Obsidian**Scoria**

Red colour from oxidation of iron during weathering

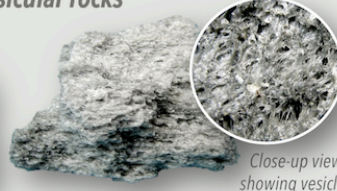
**Vesicular rocks****Pumice**

Figure 6.4 – Glassy and vesicular extrusive volcanic rocks. Obsidian is smooth with conchoidal fracture. Despite its dark color, it is felsic in composition. Scoria and pumice are highly vesicular. Scoria tends to be formed from basaltic magma, while pumice forms from felsic magma. Image credit: Karla Panchuk after Steven Earle; Photos by R. Weller/Cochise College, CC BY-NC-SA.

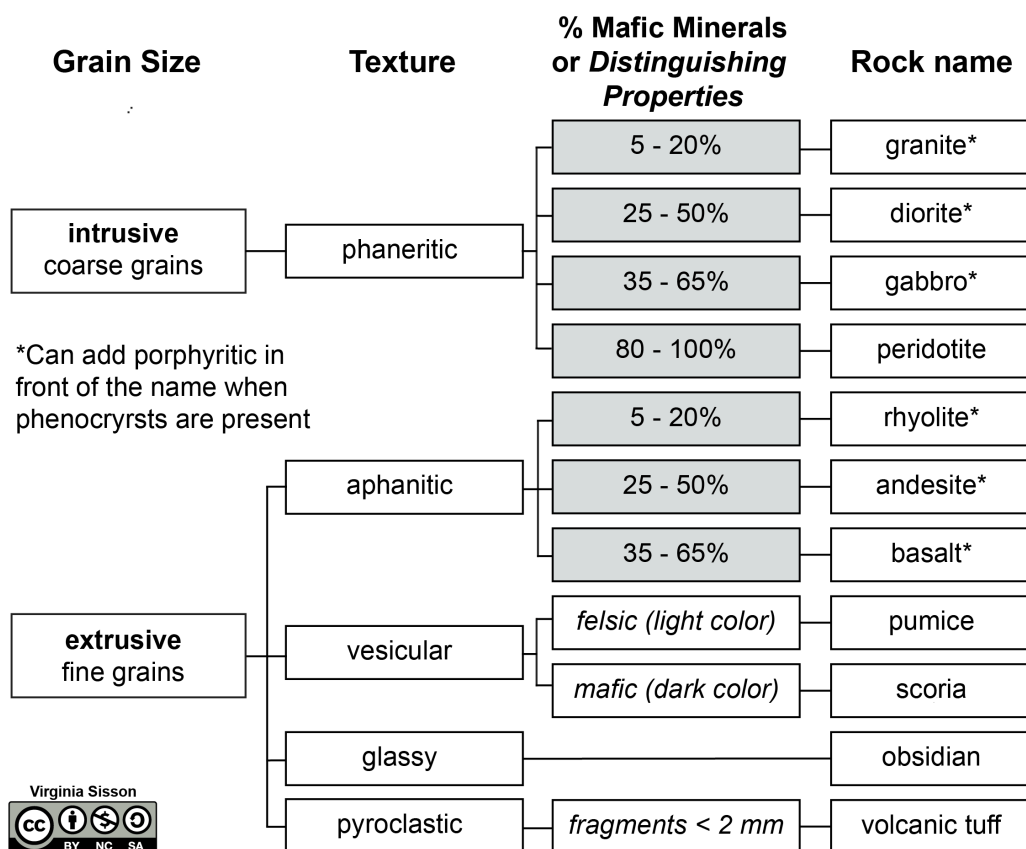


Figure 6.5 Flow chart for identifying igneous rocks using grain size, texture, minerals and percent mafic (dark) minerals: Image credit: Virginia Sisson adapted from Stuart McKinnon, CC BY-NC-SA.

Exercise 6.2 – Igneous Rock Identification

Using figures 6.2 – 6.5, identify the set of igneous rocks given to you by your instructor. Fill in the table in Figure 6.6.

Sample Number	Texture	Composition	Minerals you can see	Rock Name

Figure 6.6 – Table to fill in for igneous rock identification.

6.3 Creating Magma

The temperatures needed to melt a rock to create magma are between 600 and 1,300 °C (1,100 and 2,400 °F), depending on the rock's composition and its depth (pressure). With normal temperature gradients in Earth, it is almost impossible to reach these temperatures. In your lecture class, you'll learn about decompression melting and fluid-assisted melting. It is impossible to demonstrate these in a lab setting. We can, however, simulate one melting process which results in creation of magmas.

Partial melting is when some minerals in a rock melt before others do. Most rocks are made up of different minerals, and each mineral has a different melting temperature. In general, minerals with more silica will melt before those with less silica. During partial melting, minerals with lower melting points will melt first; while minerals with higher melting points remain solid. The melt (magma) composition is "enriched" with the minerals that have melted, and the remaining solid (rock) is "depleted" in the minerals that have melted. For example, if a mafic rock undergoes partial melting, the magma created is intermediate. The resulting magma has more (enriched in) silica, and the remaining rock has less (depleted in) silica.

Exercise 6.3 – Partial Melting

Let's construct an analog for partial melting.

- Place a scoop of cookie dough or chocolate chip ice cream into a beaker. Place the beaker on a heat source and slowly increase the temperature. What happens to the ice cream when compared to the cookie dough chunks and/or chocolate chips?

-
-
- b. Is your melt depleted or enriched in ice cream?
 - c. Is your solid depleted or enriched in ice cream?
 - d. **Critical Thinking:** If the chocolate chip ice cream represents a diorite, what minerals chocolate chips represent? What type of magma (melted ice cream) is generated?
-
-

6.4 Volcanoes

Volcanic eruptions are one of Earth's most dramatic and destructive agents of change. Powerful explosive eruptions drastically alter land and water for tens of kilometers around a volcano. Also, droplets of sulfuric acid erupting into the stratosphere can temporarily change Earth's climate. Volcanic eruptions often force people living near volcanoes to abandon their land and homes. Those living farther away are likely to avoid complete destruction, but these cities and towns, crops, industrial plants, transportation systems, and electrical grids can still be damaged by tephra, ash, lahars, and flooding.

Fortunately, volcanoes often exhibit unrest that allows eruptions to be anticipated and warnings sent to at-risk communities. The warning time preceding volcanic events typically allows sufficient time for nearby communities to implement response plans. Another way to predict future eruptions is to investigate the past eruptive history of a volcano.

Exercise 6.4 – Volcano Eruption Frequency

Some people have suggested that the number of volcanic eruptions is increasing and contributing to climate change. Let's look at some data. Table 6.2 shows the number of volcanic eruptions worldwide from 1992 to 2008.

Table 6.2 – Yearly volcanic eruptions from 1992-2008

Year	Number of Eruptions
1992	27
1993	27
1994	32
1995	33
1996	35
1997	26
1998	32
1999	39
2000	39
2001	33
2002	41
2003	29
2004	49
2005	46
2006	44
2007	36
2008	45

- Plot the volcanic eruption data from Table 6.2 on the blank graph in Figure 6.7.
- Do you think there is a trend in this data? Have the number of volcanic eruptions per year been increasing? Explain.

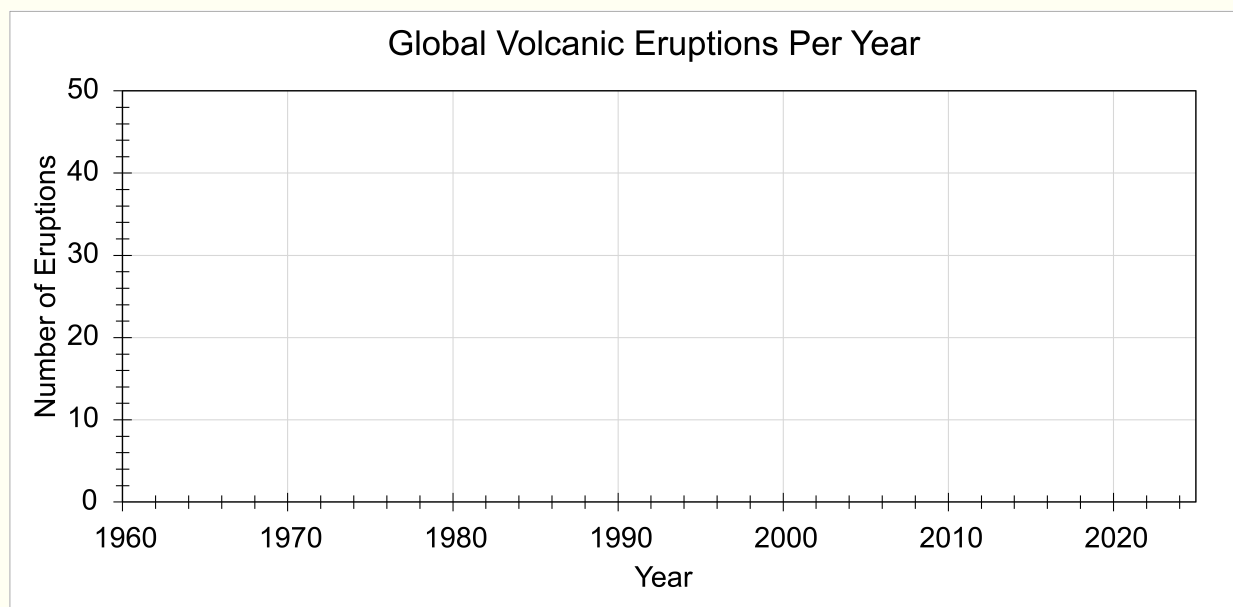


Figure 6.7 – Graph for plotting volcano eruption data from Table 6.2 and 6.3.

Sometimes people interpret data without looking at the big picture, either accidentally or by cherry-picking data points that support their point. You were only given a subset of the volcanic eruption data in Table 6.2.

- c. Table 6.3 contains the remaining data from the years before and after the data you plotted. Plot this new data on the same graph in Figure 6.7. You can use a different color if you'd like.
- d. Do you think there is a trend now that you have the complete data set? Have the number of volcanic eruptions been increasing, decreasing, or about the same? Explain.

Table 6.3 – Yearly volcanic eruptions from 1960-1991, 2009-2022

Year	Number of Eruptions	Year	Number of Eruptions
1960	35	1984	33
1961	32	1985	27
1962	29	1986	41
1963	40	1987	32
1964	29	1988	27
1965	34	1989	25
1966	35	1990	30
1967	43	1991	37
1968	32		
1969	32		
1970	34	2009	31
1971	32	2010	33
1972	30	2011	36
1973	41	2012	39
1974	27	2013	38
1975	23	2014	42
1976	29	2015	41
1977	39	2016	34
1978	25	2017	32
1979	32	2018	37
1980	41	2019	27
1981	29	2020	27
1982	32	2021	33
1983	32	2022	31

The volcanic eruption data is from the [Smithsonian Institution Global Volcanism Program](#).

Geologists monitor most of the world's volcanoes for eruptive activity, but how can past eruptions be determined, especially for events before human memories? The simplest way is to look at a detailed map around a volcano. With each eruption comes a new layer of lava that turns to igneous rock. By mapping out the igneous rocks, you can determine the volcano's eruptive history. One of the most visited volcanoes is the Big Island of Hawaii, which is actually made up of several volcanoes, with Kīlauea being the most active today. The oldest eruption on the island started about 1 million years ago and it may be actively erupting as you read this (Figure 6.8).

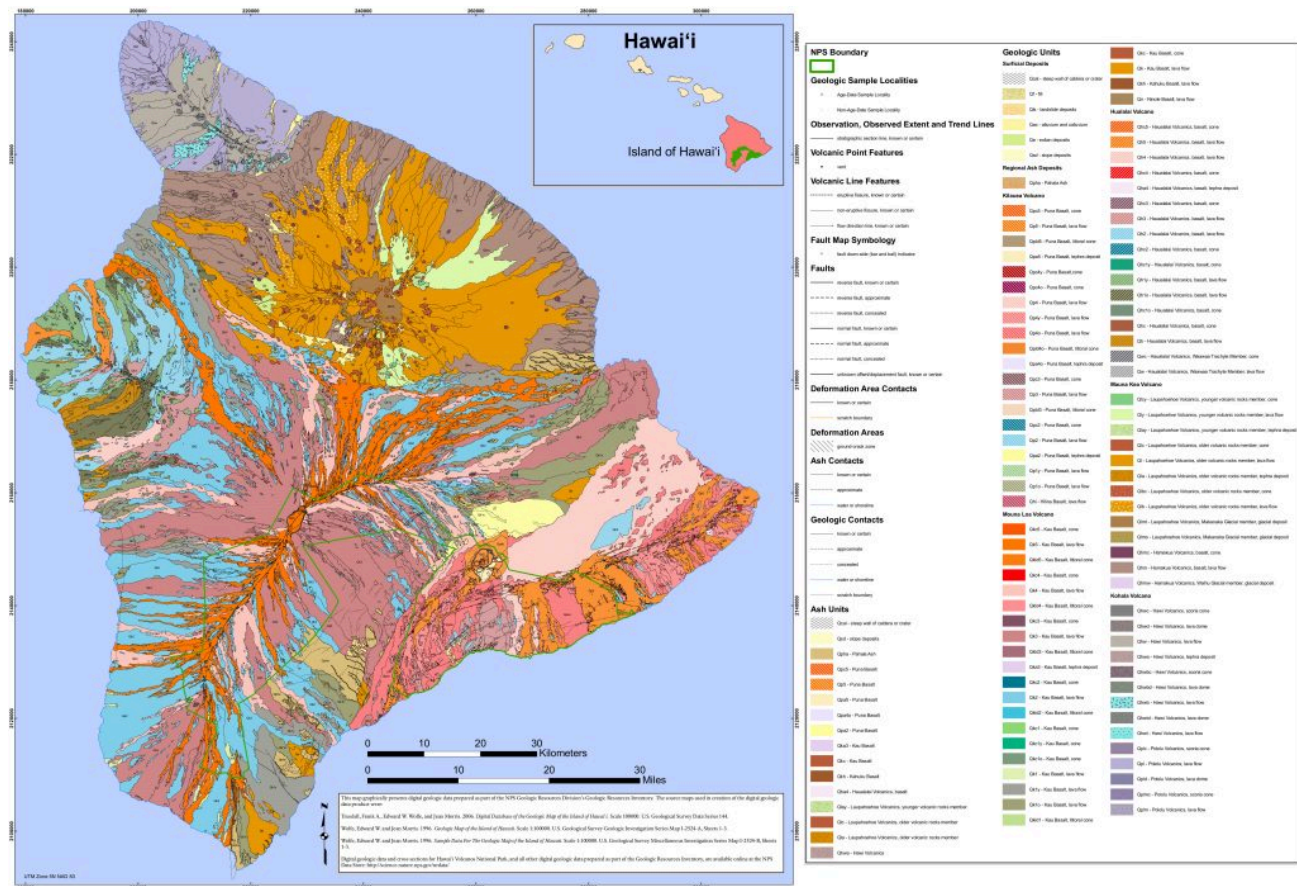


Figure 6.8 Geologic map of Hawaii showing five eruptive centers and over 90 volcanic layers (also called units). Each color indicates a different eruption unit. Note, this map will change after every eruption. Image Source: National Park Service Public Domain.

Exercise 6.5 – NASA Volcano Mapping

Volcanic mountains grow through successive eruptions of lava and other volcanic materials. Each eruption creates a new layer of rock, slowly raising the peak's elevation. In this exercise, you'll create your own volcano and map each eruption. This exercise is from [NASA JPL](https://www.nasa.gov/jpl). See their step-by-step instructions for images of each step.

Creating a volcano:

1. Use the bottom half of a petri dish.
2. Place it in the center of graph paper and trace around it with a pencil (this is your map).
3. Use a paper plate and mark north, south, east, and west on its edges and then mark north on your graph paper. This will help you remember the order of events in geographic coordinates.
4. Fill the petri dish with baking soda.
5. Place a small amount of vinegar into the petri dish and watch the eruption of simulated lava. If it doesn't flow, add more vinegar.
6. When the lava stops, quickly draw around the flow edge with a pencil.
7. Dab up the fluid with paper towels.

8. Use a thin layer of play dough to cover the entire area where lava flowed.
9. On one piece of graph paper, use a colored pencil that matches the play dough color to draw an outline representing the edge of the play dough, being sure to maintain the cardinal orientation (north, south, east, west) of the paper with the orientation of the volcano. Shade in this lava flow drawing. Make a note on the graph paper regarding the order of eruptions (which color came first).
10. Repeat the eruption process to create a total of 4 to 6 flows.
11. Trade your volcano with another group (keep your map).

Now that you have another group's volcano, imagine yourselves as a team of geologists seeing a volcano for the first time. Your job is to investigate and map this volcano that has an unknown history.

1. Grab another piece of graph paper and mark north.
2. Draw the visible layer(s) of the volcano to scale on the graph paper using a ruler and colored pencils.
 - a. How many lava flows can you see? _____
 - b. Make a list of the lava flows, starting with the youngest flow at the top and the oldest at the bottom. Example: "Top flow is a long, skinny, green flow."

- c. Can you easily determine the sequence of flows (which came first, second, etc.)? Are there some flows you can't say which are younger or older? Explain.

- d. Are there parts of any flows that might be covered? Which ones?

- e. What would you need to determine the sequence and shape of each flow? How could you get that information without lifting the play dough?

Stop here and wait for your instructor before continuing.

- f. Complete the remaining steps outlined by your instructor. Record the locations and information gained on your map and finish it. What is the sequence of flows that tells the history of this volcano?

- g. Compare your map and sequence of flows with the one from the group that originally made the volcano. Was your interpretation accurate? Explain.

If you want to live near a volcano, knowing the types of hazards is critical to evaluate the risks you'll be taking. Some volcanoes are **dormant** or **extinct** and no longer hazardous. Most countries with active volcanoes monitor their potential hazards. Active volcanoes are monitored for seismic activity (earthquakes), gases, deformation of the ground, gravity, magnetics, and thermal imaging. You can go to the [Global Volcano Network](#) to assess recent activity around the world.

Exercise 6.6 – Reading a Volcanic Hazard Map

Figure 6.9 contains a colored digital elevation model and a hazard map of the Mt. Rainier region in Washington State. For reference, Seattle is located near Puget Sound just north of this map.

- a. Do lava flows and [pyroclastic flows](#) pose a significant risk to the surrounding population? Explain

- b. What do you notice about the path [lahars](#) tend to follow in this region?

c. How far can these lahars travel? Measure on the map.

d. What could cause the failure of the Alder Dam and subsequent flooding (located on the western side of the map near the town of Elbe)?

e. Critical Thinking: What do you think is the source of water for the lahars?

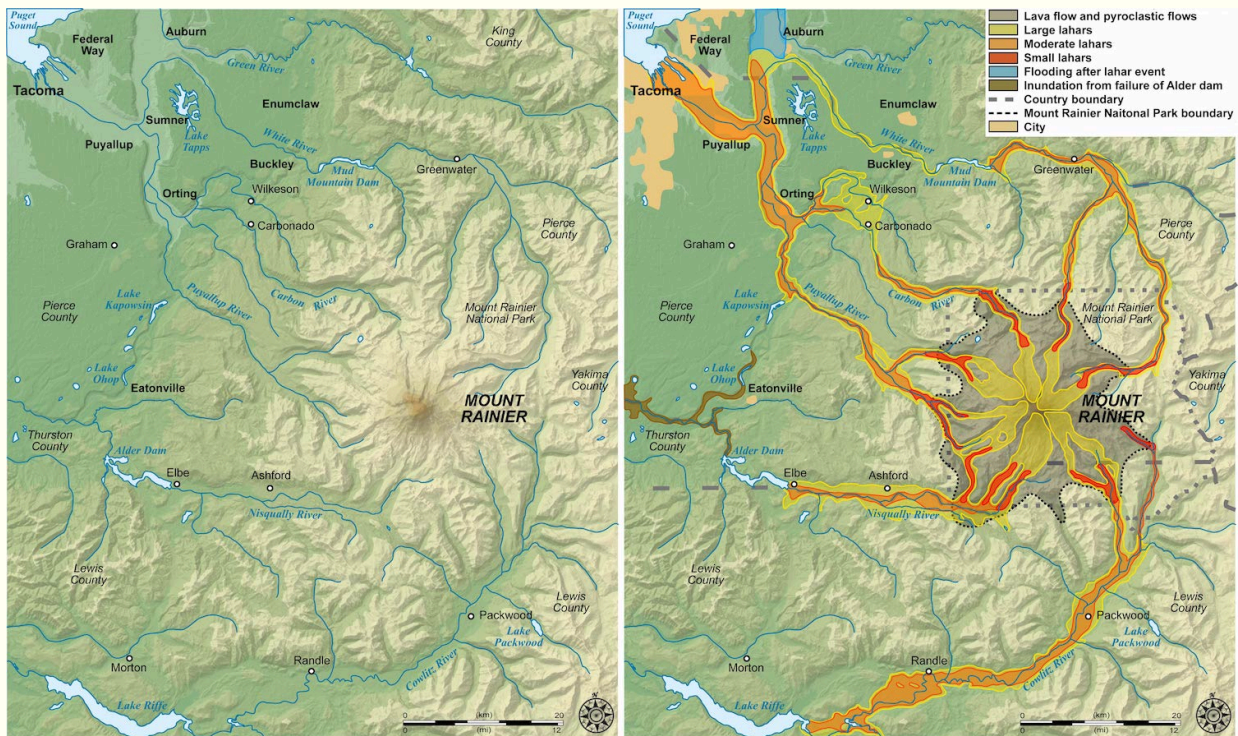


Figure 6.9 – Colored digital elevation model and volcanic hazard map of the Mt. Rainier region in Washington State. Image credit: Adapted from [Wikimedia user Sémhur](#) and the [USGS](#), CC BY-SA.

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson, Kaitlin Thomas

CHAPTER 7: WEATHERING AND SEDIMENTARY ROCKS

Differential Weathering, Rock Classification, and Depositional Environments

Learning Objectives

The goals of this chapter are to:

- Understand differential weathering
- Identify and classify sedimentary rocks
- Interpret depositional environments

7.1 Weathering

Weathering occurs when a rock is exposed to the “weather”, or to the forces and conditions at Earth’s surface. A rock exposed at the surface can experience changes in temperature, oxygen and other gases, and water. Each interacts with rocks to break them down physically and/or chemically. Physical weathering, also called mechanical weathering, is the breakdown of rocks into smaller fragments, called sediment. The mineral chemistry is not altered during physical weathering. Chemical weathering does alter the chemistry of minerals, either by dissolving minerals in a solution of water, or by replacing elements in a mineral. Chemical weathering typically results in ions (elements) remaining dissolved in a solution.

Physical and chemical weathering go hand in hand because physical weathering produces fresh surfaces for attack by chemical processes, and chemical weathering weakens the rock so that it is susceptible to physical weathering.

Exercise 7.1 – Weathering Rates

The weathering rate of rocks and minerals is affected by the composition of the atmosphere, temperature and rainfall rates, even at a local level. Below are the results of a study of marble gravestones in Australia (Figures 7.1 and 7.2). The data is from two areas: an urban residential area in Sydney and an industrial area in Wollongong (65 km or 45 miles south of Sydney). The year is when the gravestones were inscribed. The surface reduction is a measurement of how much weathering has occurred on the gravestones’ surface since they were emplaced.

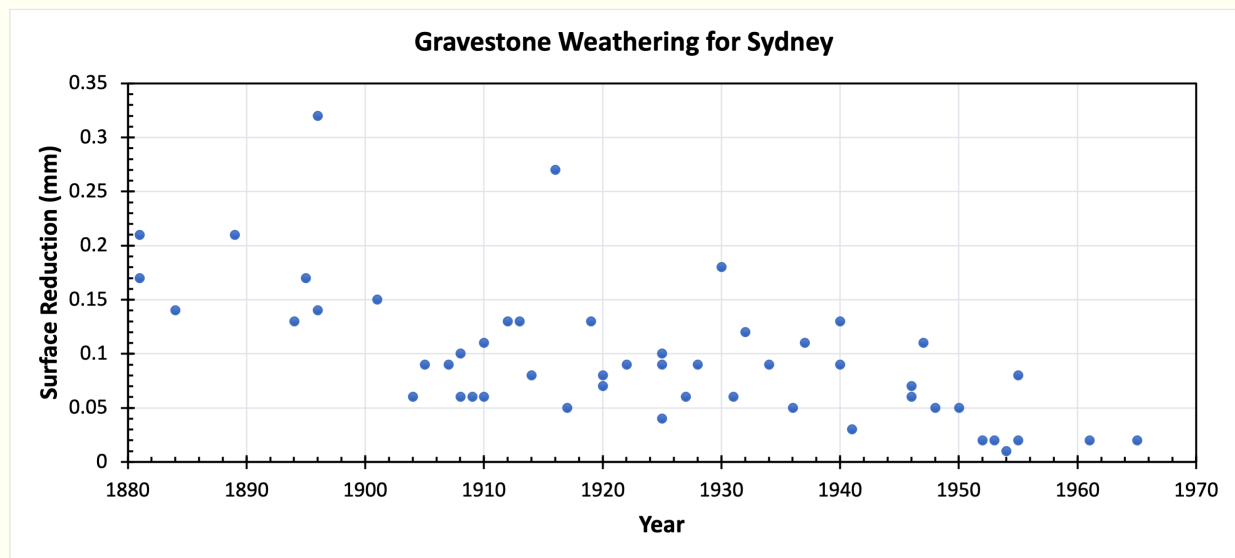


Figure 7.1 – Gravestone weathering for an urban residential area in Sydney, Australia. Data from Dragovich (1986).

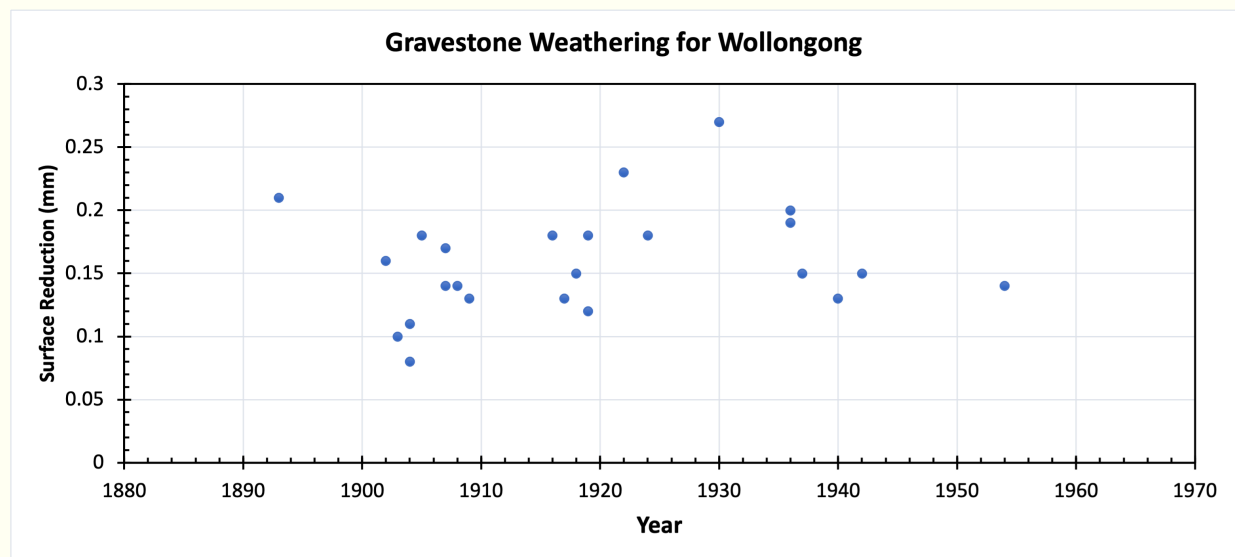


Figure 7.2 – Gravestone weathering from an industrial area in Wollongong, Australia. Data from Dragovich (1986).

- a. Describe the relationship between weathering and age of the gravestones in Sydney.

- b. What is the relationship between weathering and age of the gravestones in Wollongong? How does it compare to Sydney?

Another way to look at this data is to analyze the weathering rate per 100 years (Figures 7.3 and 7.4), but we don't have 100 years worth of data for each gravestone. So, we extrapolate the available weathering data to 100 years, assuming a consistent weathering rate for each gravestone. For example, the gravestone in Wollongong that was emplaced in 1940 would only be a 46-year record (measurements were taken in 1986). In that 46-year period, the gravestone weathered a total of 0.13 mm, or about 0.0028 mm/year. Multiply the yearly weathering rate by 100 and you get a weathering rate of 0.28 mm/100 years.

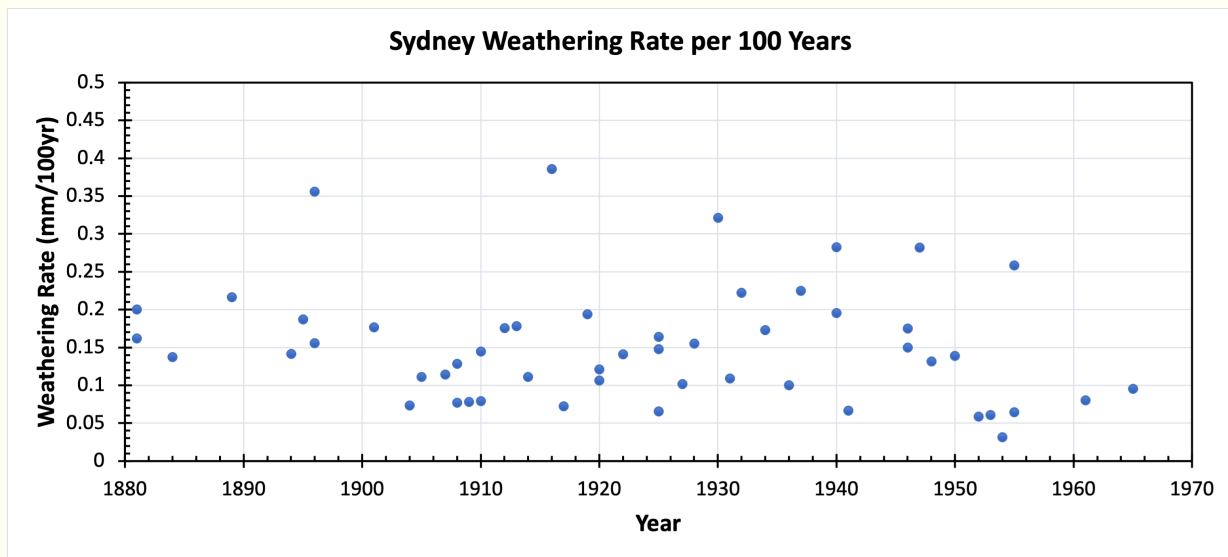


Figure 7.3 – Weathering rate per 100 years for Sydney, Australia.

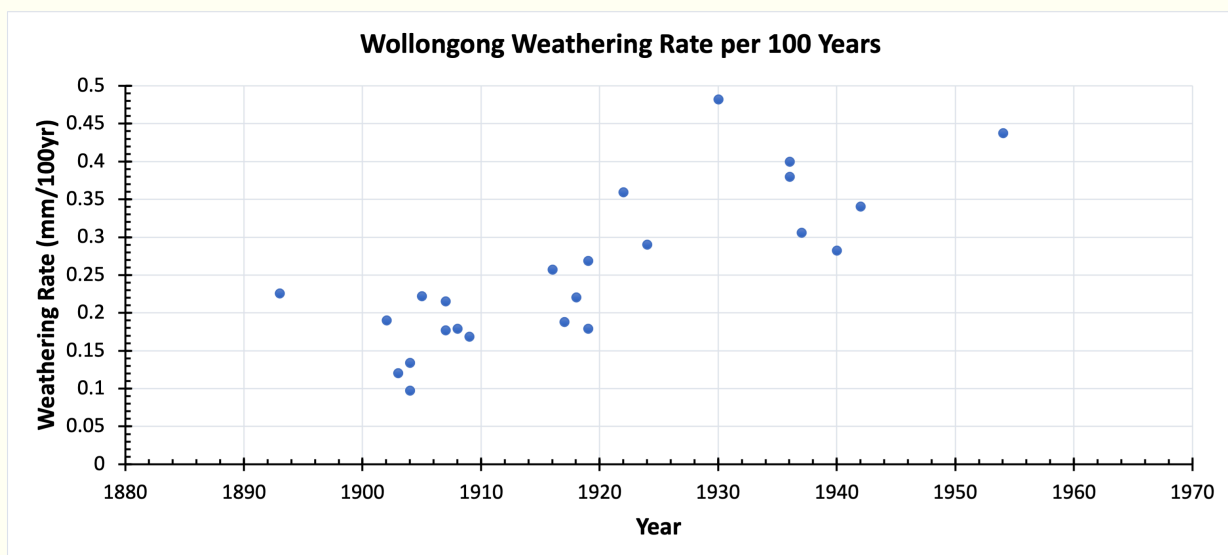


Figure 7.4 – Weathering rate per 100 years for Wollongong, Australia.

- c. What is the average weathering rate per 100 years for Sydney? Draw a line of best fit on Figure 7.3.

- _____
- d. Has the rate of weathering changed for Sydney? If so, can you locate when the change occurred?
- _____
- _____
- _____
- e. What is the average weathering rate per 100 years for Wollongong? Draw a line of best fit on Figure 7.4. _____
- f. Has the rate of weathering changed for Wollongong? If so, can you locate when the change occurred?
- _____
- g. On average, gravestones are about 4 inches thick (102 mm). Using the weathering rate for the 1940 gravestone in Wollongong of 0.28 mm/100 years (0.0028 mm/year), how many years would it take for this gravestone to completely weather away? _____
- h. **Critical thinking:** Compare the weathering rate over time for both sites. Which are the principal factors controlling weathering rate between the two sites? Do you think this similarity or difference will continue in the future?
- _____
- _____

This exercise is adapted from [G.S. Hancock and C.M. Bailey](#).

7.2 Sediment Erosion, Transport, Deposition, and Lithification

What happens after weathering? The particles need to be moved, or eroded. Sediment particles that were physically weathered are moved by water, wind, and ice. When the water or wind slows down, or when the ice melts, the sediment stops moving and is deposited. These mechanisms can transport sediment hundreds of kilometers. For ions that were chemically weathered, they can precipitate out of the solution under certain conditions, forming solid particles that can be deposited.

In all cases, sediments need to undergo **lithification** to transform from loose grains to a solid rock. Typically, two steps are involved in turning sediment into a sedimentary rock; **compaction** and **cementation**. When grains are deposited, they typically have empty spaces between them called pores (**porosity**). Compaction reduces porosity by bringing the grains closer together. The best analogy to think about is your garbage can at home. When the garbage can is full, do you change the bag right away or do you push down on it to create more room? By pushing down on trash, you reduce the space between the pieces of garbage and create more room at the top; this is compaction. Sediments work the same way, but what's causing the compaction is the accumulation of more sediment on top of the previously deposited material. The more sediment piled on top, the more compact the sediment beneath it becomes.

Cementation is a process that happens during either at the surface or during compaction. As sediments interact with water, minerals precipitate in pore space acting as a glue that holds the sediment together.

During compaction, water is squeezed out of the pore spaces; this enhances cementation. The common minerals that make up cement are **calcite**, **quartz**, and **pyrite**.

Exercise 7.2 – Observing Sedimentary Rocks

Your instructor has provided you with a set of rocks. Continuing with our ideas of classification, sort these rocks into groups based on any criteria you want to use. Your instructor may ask you to re-classify the materials several times using different criteria.

- a. Which criteria did you use? Why?

- b. Did you need to reclassify your samples? If so, which criteria changed?

7.3 Sedimentary Rock Classification

Sedimentary rocks (Figure 7.5) are classified as **clastic**, **chemical**, and **organic** based on how they form. The most common way sedimentary rocks form is when other rocks weather into small particles and are transported by wind, water, or ice to an area where they are deposited. These are called clastic sedimentary rocks and are classified based on their grain size. Sedimentary rocks can also form through chemical or organic processes. If you have a body of water containing dissolved salt and then that water evaporates, it will leave behind the salt as a solid mineral form called a precipitate, which is a chemical sedimentary rock. Organic sedimentary rocks form from the accumulation of **organic debris**. This organic material would need to be buried very quickly, so it doesn't **decay**. Organic material in sedimentary rocks is where coal, oil, and natural gas come from. Then, there are sedimentary rocks that we can classify as biochemical. For example, **foraminifera** are tiny, single-celled organisms that build shells out of calcium carbonate. After they die and decay, their shells may sink to the bottom of the ocean and accumulate to form a sedimentary rock. In this case, biological processes caused the chemical precipitation of the mineral for the shell, but it doesn't contain organic compounds, so we call it **biochemical**.

Inorganic Clastic Sedimentary Rocks						
Texture	Grain size	Composition	Comments	Rock name	Map symbol	Picture
Clastic (fragmental)	Pebbles, cobbles, and/or boulders in a matrix of sand, silt and/or clay	Mostly quartz, feldspar, and clay minerals; may contain fragments of other rocks and minerals	Rounded fragments	Conglomerate		
			Angular fragments	Breccia		
	Sand (0.063 to 2 mm)		Fine to coarse in a variety of colors	Sandstone		
	Silt (0.039 to 0.063 mm)		Very fine grained, massive, usually dark	Siltstone		
	Clay (<0.0039 mm)		Compact, brittle, usually dark	Shale		
Chemically and/or Organically Formed Sedimentary Rocks						
Texture	Grain size	Composition	Comments	Rock name	Map symbol	Picture
Crystalline	Fine to coarse grains	Quartz	Chemical precipitates and evaporites	Chert		
		Halite		Rock salt		
		Gypsum		Rock gypsum		
		Dolomite		Dolostone*		
Crystalline or bioclastic	Microscopic to very coarse	Calcite	Biologic precipitates or cemented shell fragments	Limestone*		
Bioclastic	Clay (< 0.0039 mm)	Carbon	Black, compacted plant remains	Coal		
Bioclastic	Clay (< 0.0039 mm)	Clay and kerogen	Dark, may have oily smell or burn	Oil shale		

Other types of sandstone are arkose and graywacke. Varieties of limestone include chalk, coquina, micrite, travertine, oolite, tufa, and fossiliferous limestone.

* These react with dilute acid.



Figure 7.5 – Sedimentary rock classification table. Also shown are the US Geological Survey standard patterns for these rock types. Image credit: Virginia Sisson, CC BY-NC-SA.

The size and shape of grains within sedimentary rocks can also help you interpret that sediment's history (Figure 7.6). When all the grains in the rock are about the same size, it is called **well-sorted**. Usually, sediment needs to travel a far distance from its source to be well-sorted. In contrast, poorly sorted sediment is deposited very close to its source. The **rounding** of sediment grains is also an indicator of how far the sediment traveled. Grains that have smooth edges are considered well-rounded and have traveled a far distance. These grains start out with rough edges and become smoother as they travel further and further. In contrast, grains with sharp edges are considered angular and have not traveled a far distance (Figure 7.6).

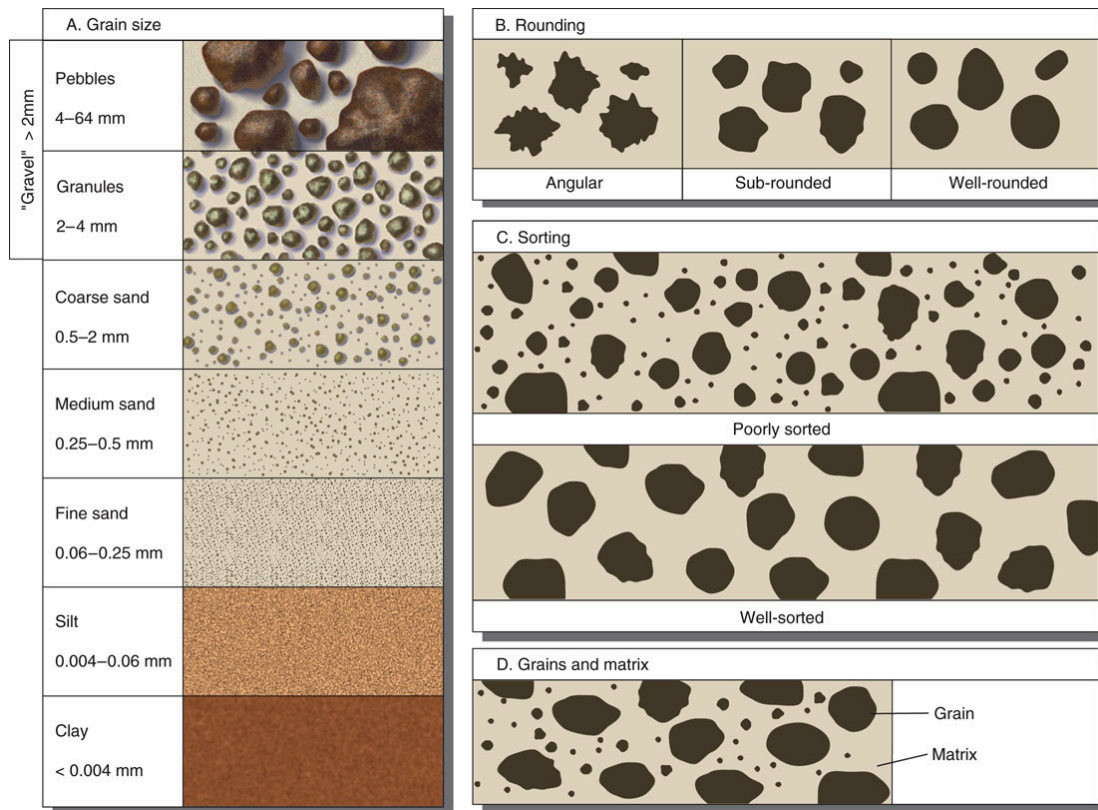


Figure 7.6 – Grain size, rounding, and sorting of sedimentary rocks. Image credit: National Park Service, Public Domain.

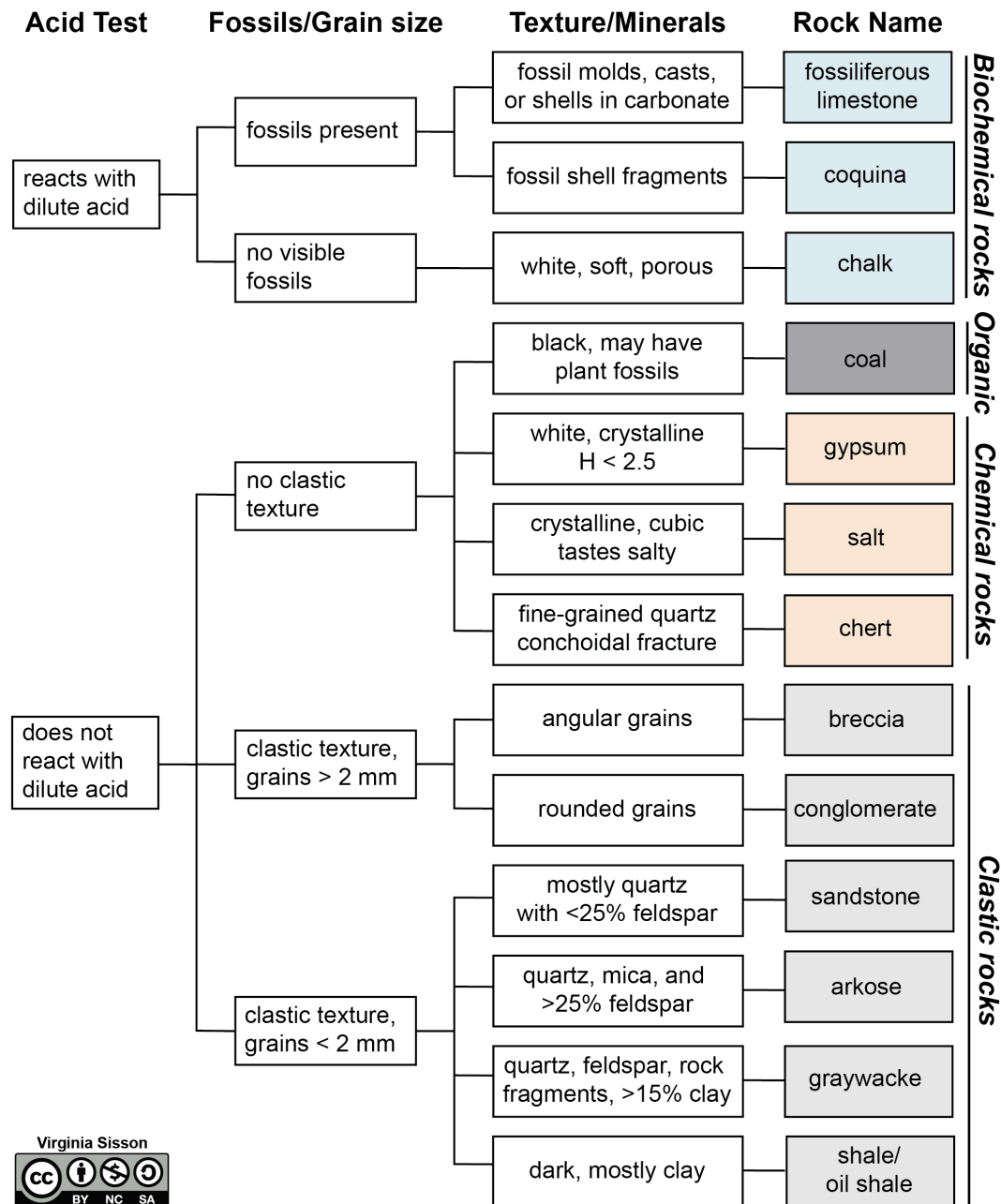


Figure 7.7 Flow chart for identifying sedimentary rocks using reaction to acid, texture, mineralogy and other features to identify sedimentary rocks. Image credit: Virginia Sisson CC BY-NC-SA.

Exercise 7.3 – Identifying Sedimentary Rocks

Your instructor has given you a set of unknown sedimentary rocks. Identify the characteristics and names of these rocks using Figures 7.5 and 7.6 and fill out Table 7.1.

Table 7.1 – Sedimentary rock identification					
Sample	Classification	Grain Characteristics (size, shape, sorting)	Minerals you can see	Rock Name	Depositional Environment

7.4 Depositional Environments

Sedimentary rocks contain clues that tell you about the environment was like at the time of their deposition. Figure 7.7 contains imagery for several common sedimentary environments. Interpreting depositional environments based on the sedimentary rock characteristics is a very important part of a sedimentary geologist’s job. Many environments share characteristics in their deposits with other environments; for example, deserts and beaches commonly leave behind deposits of quartz-rich, well-sorted sands. There may also be a wide variety of deposits within a single type of environment; for example, a slow-moving river may deposit silty mud in its channel, while a rapidly flowing river may deposit coarse sands and pebbles. Due to the variety in deposits and overlapping characteristics, it takes a well-trained eye to accurately determine the correct depositional environment for many sedimentary rocks.

Exercise 7.4 – Sedimentary Environments

Below, you have been provided with branching diagrams that group depositional environments based on shared characteristics (Figures 7.8 – 7.12). Note that environments grouped in one diagram are often not grouped in others. The characteristics of sediments deposited in a system are broadly controlled by the proximity of the deposit to the sediment source and how much energy is moving through the system.



Figure 7.8 – Examples of depositional environments. See note at the end of the chapter for image credits.

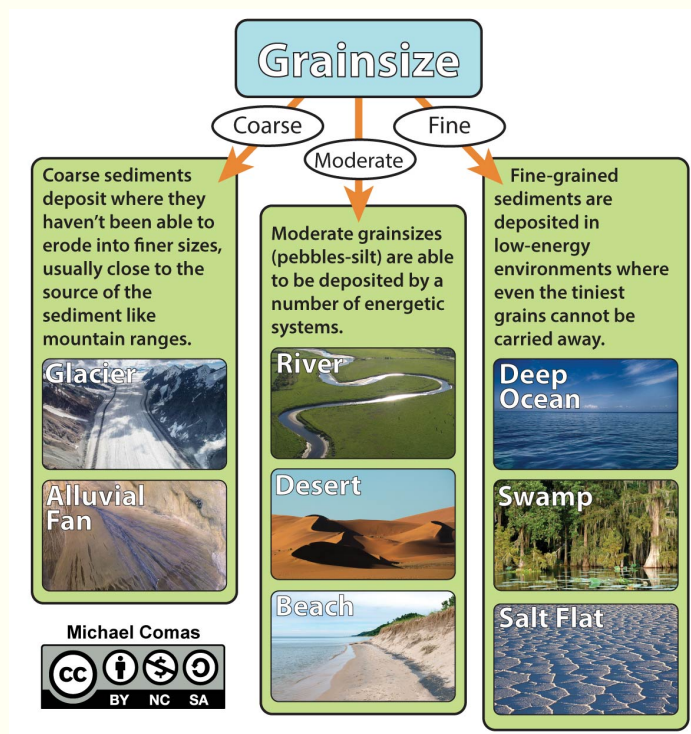


Figure 7.9 – Sedimentary environments based on grain size.

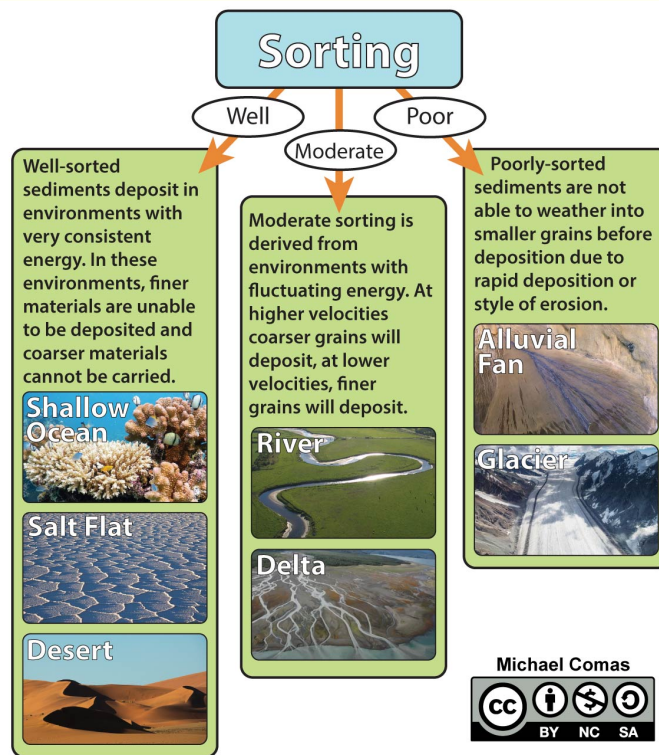


Figure 7.10 – Sedimentary environments based on sorting.

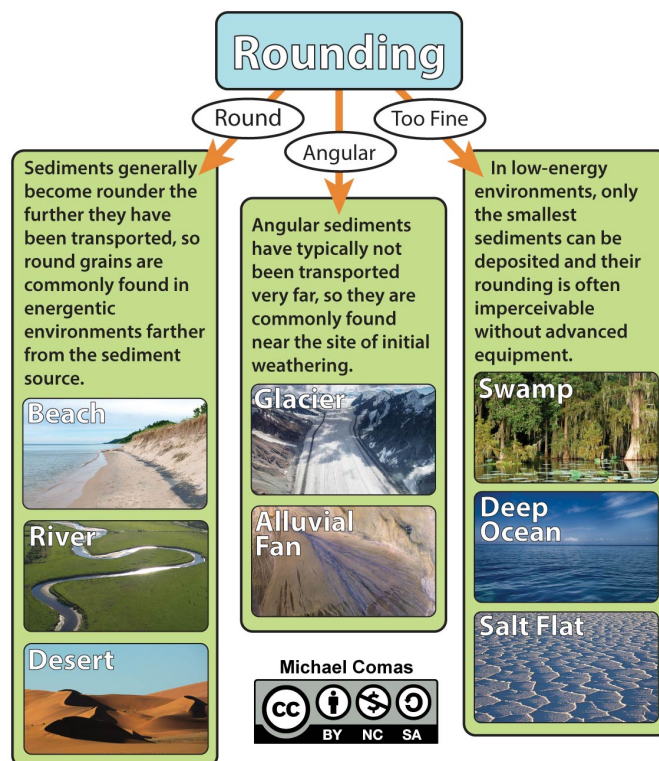


Figure 7.11 – Sedimentary environments based on rounding.

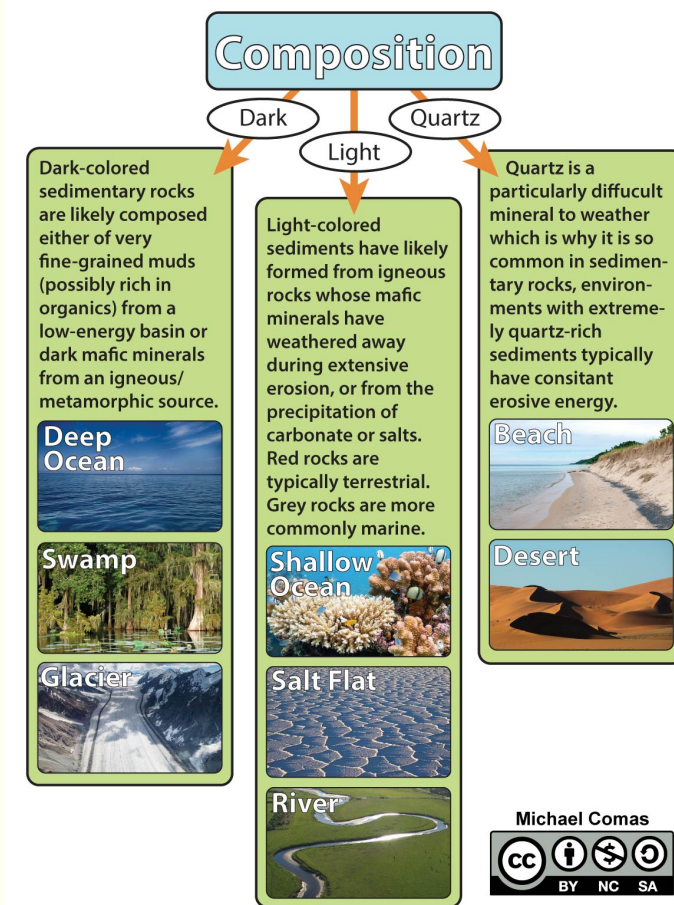


Figure 7.12 – Sedimentary environment based on composition (mineralogy).

- Use Figures 7.8 – 7.12, along with your knowledge of sediments and their structures, to help discern a possible depositional environment for each of your sedimentary rocks provided by your instructor. Fill in this information in Table 7.1.
- Critical thinking:** Which sedimentary features are useful for determining whether the depositional environment is continental versus marine? Are there any sedimentary features that will determine the sedimentary environment with just one feature?

Recall from Figure 4.2 that the most common rock type covering North America are sedimentary rocks! Now that you can recognize different rock types and interpret where they were formed, you can start to explore geologic maps and better-understand the physical world around you. This information can be used to determine where to find economic resources such as limestone for concrete, shale to make bricks, sandstone as a place for fossil fuels and drinking water, and halite deposits for salt. Or use them to help you find fossils such as the Texas state fossil wood or a dinosaur. Some use sedimentary rocks for jewelry and ornamental stones. The next exercise will explore some of the sedimentary rocks in Texas.

Exercise 7.5 – Sedimentary Rocks of Texas

Explore the [geologic map of Texas](#). Each colored polygon represents a different rock unit. Clicking on the polygon will pull up information about that rock.

- a. Look near Austin, TX for the rock labeled “Ked.” Give is the name of this rock formation?

- b. List the types of sedimentary rocks are here?

- c. Are these clastic, chemical, biochemical, or organic rocks? _____

- d. Which rock samples from your kit would be similar to those in this rock group? _____

- e. What do you think was the depositional environment? _____

- f. Look at the extent of this rock group on the map. Describe its orientation. Why do you think it has this shape?

- g. Look near Marble Falls, TX for the rock labeled “Crh” (dark brown unit to the north). Give the name of this rock formation? _____

- h. List types of sedimentary rocks are here?

- i. Are these clastic, chemical, biochemical, or organic rocks? _____

- j. Which rock samples from your kit would be similar to those in this rock group? _____

- k. What do you think was the depositional environment? _____

- l. Look at the extent of this rock group on the map. Describe its orientation. Why do you think it has this shape?

Additional Information

Exercise Contributions

Daniel Hauptvogel, Michael Comas, Virginia Sisson

References

D. Dragovitch, 1986, Weathering rates of marble in urban environments, eastern Australia; Zeitschrift für Geomorphologie, v. 30, p. 203-214

Image credits for Figures 7.8-7.12

- Glacier – [Jacob Frank, Public Domain](#)
- Desert – [Pixabay user kuloser, Public Domain](#)
- Swamp – [Wikimedia user Pierre5018, CC BY-SA](#)
- River – [Simon Ledingham, CC BY-SA](#)
- Deep Ocean – [Johann Piber, Public Domain](#)
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- Shallow Ocean – [Wallpaper Flare, Public Domain](#)

CHAPTER 8: METAMORPHIC ROCKS

Classification and Pressure-Temperature

Learning Objectives

The goals of this chapter are to:

- Classify metamorphic rocks
- Interpret metamorphic protoliths
- Evaluate pressure and temperature conditions

8.1 Introduction

Metamorphic rocks form when any pre-existing rock is altered by heat and/or pressure. The two sources of heat for metamorphism are the heat from a magma chamber and the geothermal gradient, which is the natural increase in temperature when getting deeper into the Earth. Pressure also increases with depth in the Earth, but intense pressure also occurs during tectonic plate collisions. This is why most of the world's metamorphic rocks are found in active or ancient mountain belts. Because of this, metamorphic rocks provide geologists with information on how past tectonic processes shaped our planet.

Exercise 8.1 – Observing Metamorphic Rocks

Your instructor has provided you with a set of rocks. Continuing on our ideas of classification, sort these rocks into groups based on any criteria you want to use. Your instructor may ask you to re-classify the materials several times using different criteria.

- a. List the criteria you used? Why?

- b. Did you need to reclassify your samples? If so, which criteria changed?

8.2 Heat, Pressure, and Foliation

Heat and pressure can cause several changes in rocks, such as recrystallizing minerals, creating new

minerals, and orientating minerals in a direction perpendicular to differential pressure. The orientation of minerals is the most noticeable feature when recognizing metamorphic rocks, called foliation. Heat works to “soften” minerals, allowing ions to begin migrating in and out of crystal structures. Then pressure forces the minerals to re-orientate. Heat is the most important factor, though; without heat, the rock would just break under intense pressure.

Several types of foliation are commonly seen in metamorphic rocks: gneissic banding, slaty or rock cleavage, and schistosity. As pressure increases, so does the degree of foliation. Not all metamorphic rocks exhibit foliation because some minerals change very little under metamorphic conditions (quartz, for example); these types of metamorphic rocks are called non-foliated and can be very difficult to tell apart from igneous rocks.

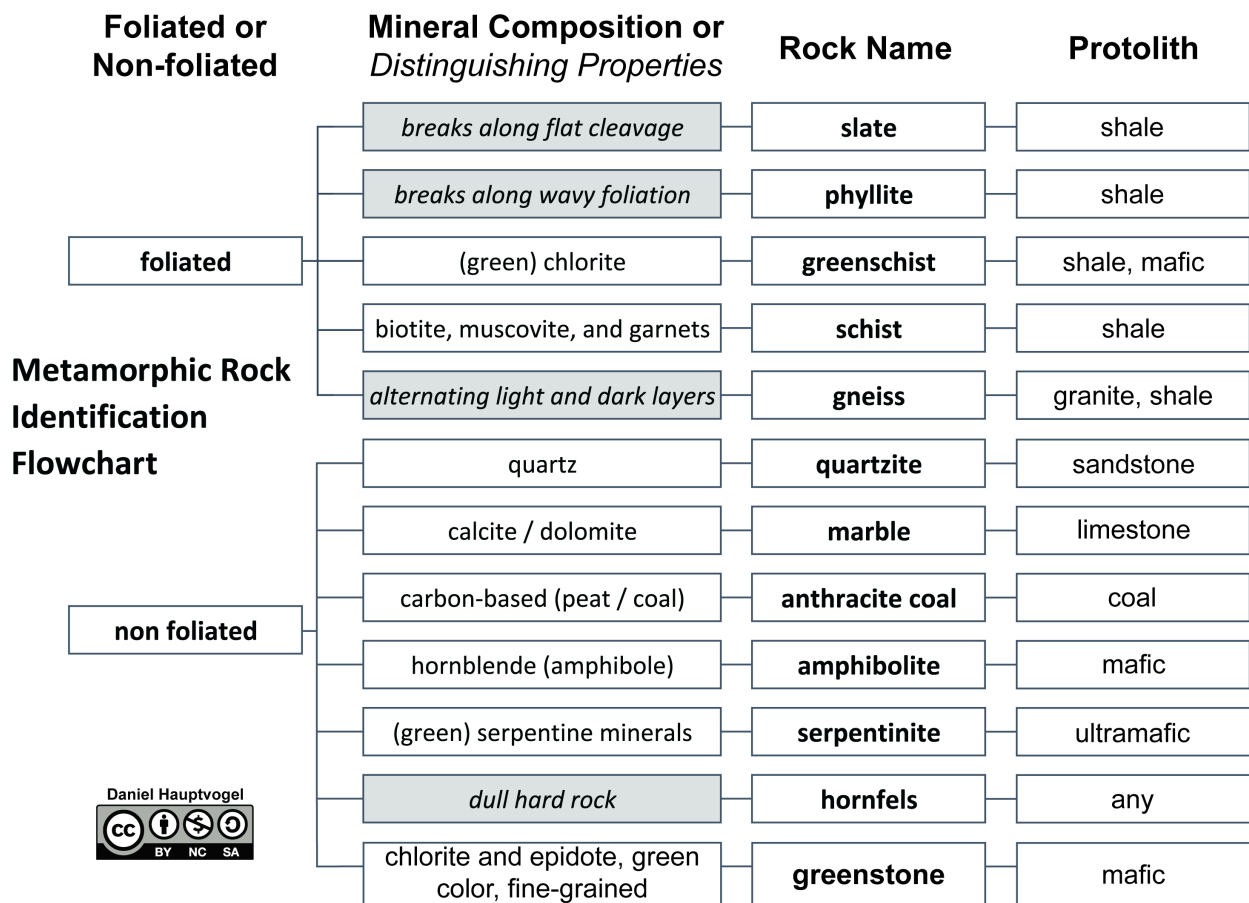


Figure 8.1 – Metamorphic rock identification flowchart. Gray-shaded boxes indicate distinguishing properties instead of mineral composition. The column for protolith indicates what the rocks were before metamorphism. Image Credit: Daniel Hauptvogel, CC BY-NC-SA, adapted from Stuart MacKinnon.

Another feature or observation that you may use for classification is the presence of certain (**index**) minerals. There are many more minerals in metamorphic rocks than you learned in Chapter 3. So, we will try to make this easy for you. The different metamorphic index minerals reflect the highest temperature the rock reached during metamorphism (Figure 8.2).

One more aspect of identifying metamorphic rocks is determining the maximum temperature that the rock reached. You can either use metamorphic grade or metamorphic facies. In this lab book, we will focus on relative metamorphic grade from low to high.

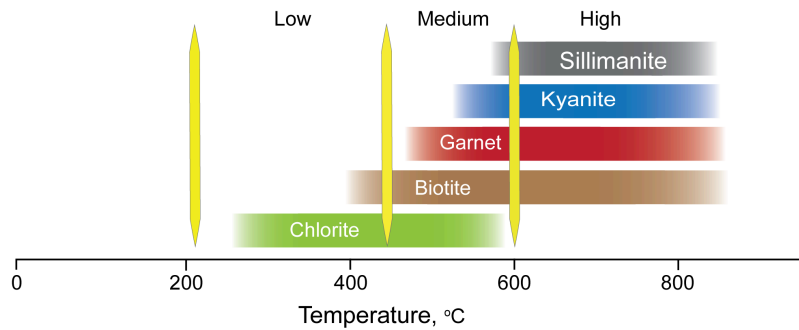


Figure 8.2 – Minerals used to interpret temperature ranges of metamorphic rocks. These minerals are for metamorphosed shales. Also shown as vertical yellow lines are the approximate boundaries for low, medium and high metamorphic grade. Green is for low-grade rocks that have chlorite. As temperature increases, biotite (brown) begins to form. As the temperature continues to increase, medium-grade rocks will have garnet (red) and kyanite (blue). At the highest grade, sillimanite appears, and then the rocks begin to melt. Image credit: Virginia Sisson, CC BY-NC-SA.

Exercise 8.2 – Identifying Metamorphic Rocks

Your instructor has given you a selection of metamorphic rocks. Use Figure 8.1 and 8.2 to help you identify them and fill in Table 8.1. Unlike igneous and sedimentary rocks, you need to determine whether or not they are foliated as the first step. Then, identify the minerals and any other distinguishing properties. Protolith will be filled in during the next exercise.

Table 8.1 – Metamorphic rock identification

Sample	Foliated or Non-foliated	Minerals you can see	Rock Name	Grade (L, M, H)	Protolith

8.3 Protoliths

What a metamorphic rock was before metamorphism is called the **protolith** (Figure 8.3). In different tectonic settings, a variety of protolith types can be metamorphosed. These rocks will be exposed to the same range of pressure and temperatures conditions, however, the metamorphic rock that results will depend on the characteristics of the protolith.

Protolith	Low Grade		Medium Grade	High Grade
Shale	Slate	Phyllite	Schist	Gneiss
Felsic	no change			Granitic Gneiss
Mafic	Greenstone		Amphibolite	
Sandstone	Quartzite			
Limestone	Marble			
Ultramafic	Serpentinite			
Organic	Anthracite			

Figure 8.3 – Metamorphic rock names for a variety of sedimentary and igneous protoliths over a range of metamorphic grades. Image credit: Virginia Sisson CC BY-NA-SA adapted from [Karla Panchuk](#), CC BY, modified after [Steven Earle](#), CC BY.

Exercise 8.3 – Understanding Protoliths

Your instructor has given each of you a rock. Half of the class has metamorphic rocks, and the other half has protoliths.

- Which type of rock do you have and what's its name? _____
- Now try to match up the metamorphic rocks with their protoliths. If you have a metamorphic rock, look for another student that has your protolith. If you have an igneous or sedimentary rock, find the rock that yours would turn into after metamorphism. Which rock did you pair up with and why?

- There is a blank column at the end of Table 8.1 for protolith. Go back and fill in the protoliths for your unknown metamorphic rocks in Table 8.1. Use Figure 8.3 to help.

8.4 Mapping Metamorphic Rocks

You've already learned that geologic maps can help you determine physical processes and geologic history of a region. The same is true for metamorphic maps as they help you figure out the direction of change of pressure and temperature in a region. They also help you determine the tectonic setting of the region. Figure 8.4 shows a metamorphic map for three different protoliths surrounding an igneous granite.

In addition to figuring the direction of temperature increase, this map also shows how fluids and chemical elements may have moved during metamorphism. In this case, silica may have moved from the granite into the marble. This also happens when copper, iron, tungsten, and other elements are deposited in economic ore deposits around igneous rocks.

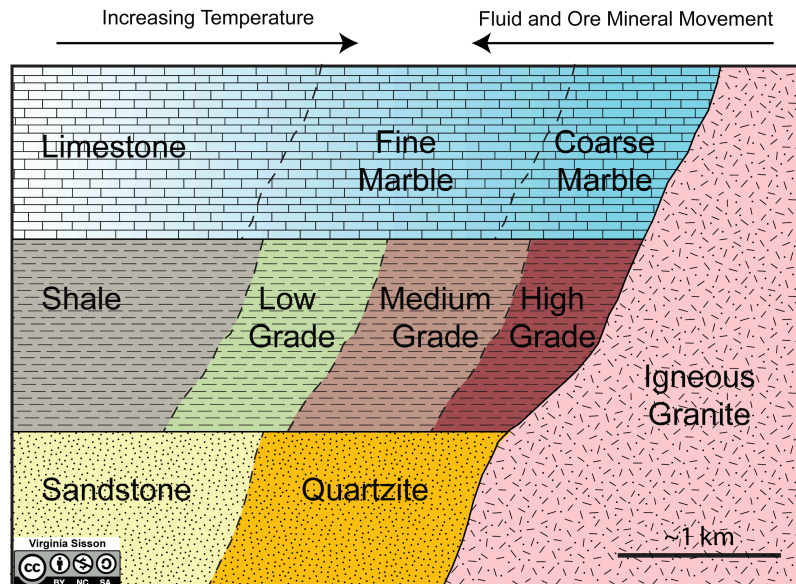


Figure 8.4 – Schematic map of an igneous granite intruded into limestone, shale and sandstone. The metamorphic temperature increases to the right. Also shown are arrows showing fluid movement and element migration away from the the granite during contact metamorphism; this shows hydrothermal metamorphism and metasomatism. Image credit: Virginia Sisson CC BY-NC-SA.

Exercise 8.4 – Creating a Metamorphic Map

One of the geology professors has found out where all the samples you looked at for this lab are found. She has mapped their locations and indicated them with a dot on the map provided by your instructor. Each location is marked with the number for the rock type found there.

To help understand this map, you need to distinguish two types of data: metamorphic grade or how hot the rock was at the peak of metamorphism, and the composition of the rock (called protolith). So, to interpret the metamorphic rock data, you will need to draw lines and color/shade different regions to interpret the geology.

Using a dashed line, draw isograds (lines of equal metamorphic grade) between low to medium and medium to high grade. You should end up with two parallel lines, but these can be at an angle to the edge of the map. This is because heat travels consistently in one direction through the Earth; so isograds are parallel lines with grade decreasing away from the heat source. Not all metamorphic rocks are useful for determining metamorphic grade, as the texture in granoblastic rocks does not change with temperature (see Figure 8.3). Also, rocks that only have one or two minerals, such as marble and quartzite, do not have any index minerals.

Drawing isograds or lines of equal metamorphic grade:

1. Draw each line as a continuous curve between or around points. Do not use short lines or lines drawn with a ruler.
2. Draw lines between all points of equal value.
3. Extend your lines all the way to the edge of the box.
4. Completely erase any mistakes or stray lines.

Next, draw solid lines between and around different rock compositions/protoliths. The different compositions you have looked at include organic, calcareous, shales, felsic (sandstone/granite), and mafic rocks. For simplicity, you can group the organic with the shales as organic matter is often deposited with shales in marshes.

Shading the composition (rock type or protoliths)

1. Use colored pencils to shade the different rock protoliths.
2. Include the colors in the legend/key on the side or bottom of the map.
3. Press lightly with your colored pencil using the side of the pencil and not the tip.
4. Hold the pencil toward the back/end of the pencil, far away from the tip.
5. Apply pressure evenly the entire time you are shading the rock protolith.
6. Move the pencil back and forth in the same direction across the entire page (do not shade up-down in one section and left-right in another section).
7. Completely shade the entire area – leave no area uncolored.

Next, lightly shade the area for each composition. A suggested color scheme is green = mafic, blue = calcareous (limestone), and yellow = felsic/shale/organic. The boundaries between the protoliths can be as small bodies shown as elongated lenses (not circles) or extend across the entire map.

After you have completed your map, answer these questions.

- a. Is this regional or contact metamorphism? Hint: look at the rock fabric and the scale of the map.

- b. Now that you have determined if this is regional or contact metamorphism, what do you think was the tectonic setting? Explain.

- c. Often, geologists want to know the **geothermal gradient** in a region. Use Figure 8.2 in to determine the temperature for each grade. What is the temperature range for this region? _____

- d. Next, divide the temperature range by the distance to get the horizontal geothermal gradient across your map. _____

8.5 Mineral Stability and Assemblages

Investigating metamorphic rocks is like being a detective to determine how deep and how hot rocks have been. Geoscientists call this **geothermobarometry**. One of the tools used to determine these variables are **petrogenetic grids** (Figure 8.5). These are x-y plots for the stability ranges of metamorphic minerals and mineral assemblages. The first petrogenetic grids were constructed by Bowen in the 1940 using experimentally determined mineral stability ranges that are plotted as metamorphic reaction boundaries to produce a petrogenetic grid for a particular rock composition. The regions of overlap of the stability fields of minerals form equilibrium mineral assemblages used to determine the pressure-temperature conditions of metamorphism.

Exercise 8.5 – Pressure and Temperature in Metamorphism

Geologists like numbers. For metamorphic rocks, the two most important numbers are the temperature that it formed at as well as the pressure. These are related by metamorphic reactions (lines on Figure 8.5). There are several types of metamorphic reactions. Some involve dehydration (loss of OH^- ions), others are solid-state reactions such as polymorphic transitions, and others involve hydration (addition of OH^- ions). On Figure 8.5, there are many metamorphic reactions shown by lines across the pressure-temperature grid. These are generally written with the reactants on the left side and the products on the right side. This is true for all reactions that are relatively vertical on this diagram.

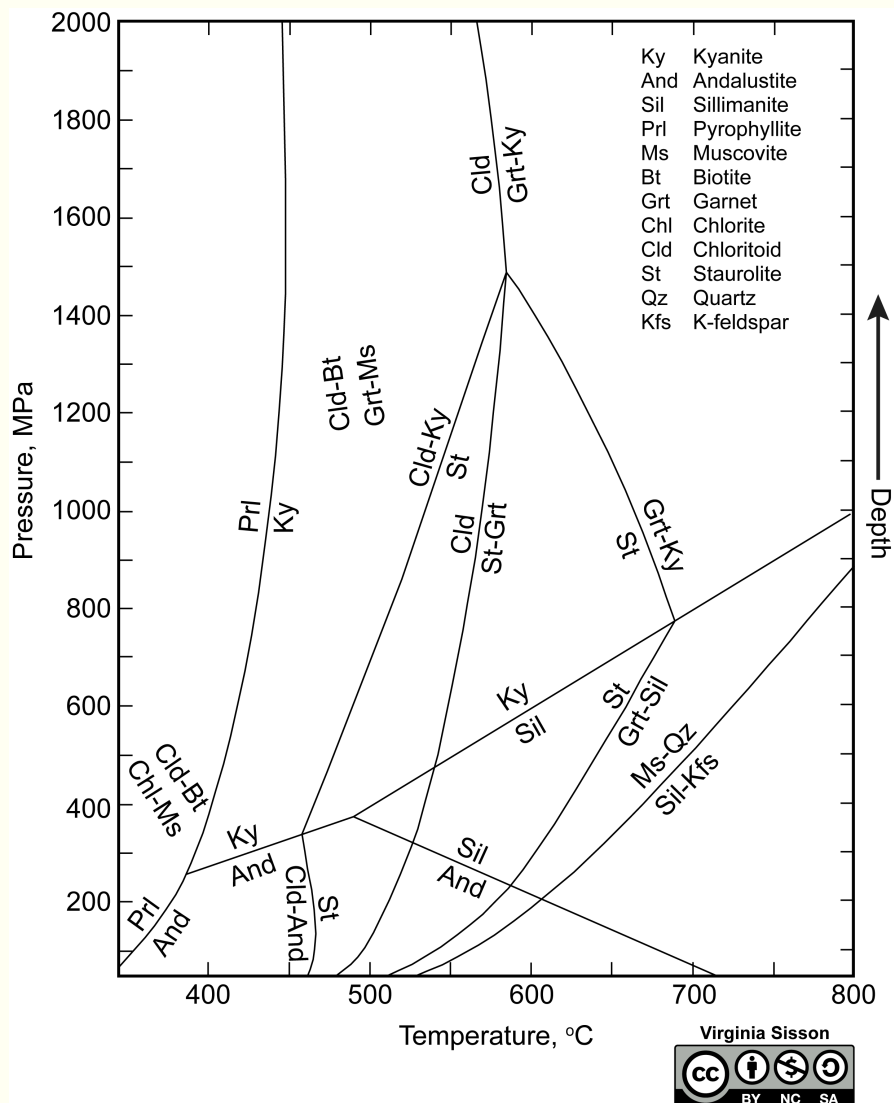


Figure 8.5 – Graph of temperature and pressure for rocks with a shale protolith. Petrologists call these petrogenetic grids. In the upper right, there is a list of minerals and their abbreviations. Image credit: Virginia Sisson CC BY-NC-SA adapted from Spear and Chaney (1989).

Table 8.2 – Minerals in pelitic metamorphic rocks

Abbreviation	Mineral	Chemical Formula
Ky	Kyanite	Al_2SiO_5
And	Andalusite	Al_2SiO_5
Sil	Sillimanite	Al_2SiO_5
Prl	Pyrophyllite	$\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$
Ms	Muscovite	$\text{KAl}_2(\text{AlSi}_3)\text{O}_{10}(\text{OH})_2$
Bt	Biotite	$\text{KFe}_3(\text{AlSi}_3)\text{O}_{10}(\text{OH})_2$
Grt	Garnet	$\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$
Chl	Chlorite	$\text{Fe}_5\text{Al}(\text{AlSi}_3)\text{O}_{10}(\text{OH})_8$
Cld	Chloritoid	$\text{FeAl}_2\text{SiO}_5(\text{OH})_2$
St	Staurolite	$\text{Fe}_2\text{Al}_9\text{Si}_4\text{O}_{23}(\text{OH})$
Qz	Quartz	SiO_2
Kfs	K-feldspar	KAlSi_3O_8

- Identify one reaction that involves dehydration (loss of OH). _____
- Write out the full chemical formula for this reaction. _____
- How much water (OH) was released during the reaction? _____
- Is the slope of this line steep or shallow? _____
- Identify one solid state (polymorphic) reaction (chemical formula remains the same).

- Is the slope of this line steep or shallow? _____
- What can you conclude about what happens to water (OH) during metamorphism?

- Low grade shales contain a dark green mica, chlorite. Those with a brownish color contain biotite. On Figure 8.5, color the area where rocks would contain chlorite and lack biotite. This would be the pressure-temperature conditions for slate.
- In a different color, color the area where rocks contain biotite but not garnet. This would be a phyllite.
- In a third color, color the area where rocks contain garnet and muscovite. This would be the pressure and temperatures for a schist.
- Give the range of temperature and pressure conditions for slate, phyllite, and schist.
 - Slate: _____
 - Phyllite: _____
 - Schist: _____
- To better constrain the pressure that these rocks formed at, you need some other mineral species in your samples. In most regionally metamorphic terrains, this is kyanite. If the rocks you are investigating have kyanite, at what pressure did they form? Explain.

-
- m. In the Central Texas region, especially near Inks Lake State Park, you can find sillimanite and muscovite in schist and gneissic rocks with no K-feldspar. What is the range of pressure that these rocks could occur at? _____
- n. **Critical Thinking:** In some regions, there are changes in the alumino-silicates (Ky, Sil, and And) with metamorphic grade. We can use these to find changes in pressure. So, if your phyllite has andalusite and your schist has kyanite, what probably happened to the pressure during metamorphism. What type of tectonic setting would this probably be?
-
-

Additional Information

Exercise Contributions

Virginia Sisson and Daniel Hauptvogel

References

Bowen, Norman (1940) Progressive Metamorphism of Siliceous Limestone and Dolomite. The Journal of Geology. 48: 225–274. [doi:10.1086/624885](https://doi.org/10.1086/624885)

Spear FS, Cheney JT (1989) A petrogenetic grid for **pelitic** schists in the system SiO₂-Al₂O₃-FeO-MgO-K₂O-H₂O. Contributions to Mineralogy and Petrology 101: 149-164. <https://doi.org/10.1007/BF00375302>

CHAPTER 9: EARTHQUAKES

Seismic Waves, Hazards, and their Distribution

Learning Objectives

The goals of this chapter are to:

- Understand earthquakes and their associated hazards
- Use seismic waves to locate earthquakes
- Evaluate earthquakes related to induced seismicity

9.1 What are Earthquakes?

An earthquake is the shaking caused by breaking and movement of rocks beneath Earth's surface. Why does the Earth move? When it is under stress, it deforms, then breaks and two sides slide past each other. Because most rock is strong (unlike loose sand), it can withstand a significant amount of stress without breaking. But every rock will rupture (break) once that limit is reached. For the case of rocks within the Earth, the rock breaks at depth and there is displacement along the rupture surface. This release of built-up elastic energy radiates away as seismic waves. The magnitude of the earthquake depends on the extent of the area that breaks (the area of the rupture surface) and the average amount of displacement (sliding).

In Chapter 2 you discovered that earthquakes occur near plate boundaries. Both divergent and transform boundaries have shallow earthquakes, whereas subduction zones can have deep earthquakes. But not all earthquakes occur along plate boundaries (Figure 9.1).

Exercise 9.1 – Observing Earthquake Hazard

Earthquakes pose a significant risk to the destruction of infrastructure and buildings and loss of life. Figure 9.1 is an earthquake hazard map of the U.S. Answer the questions below.

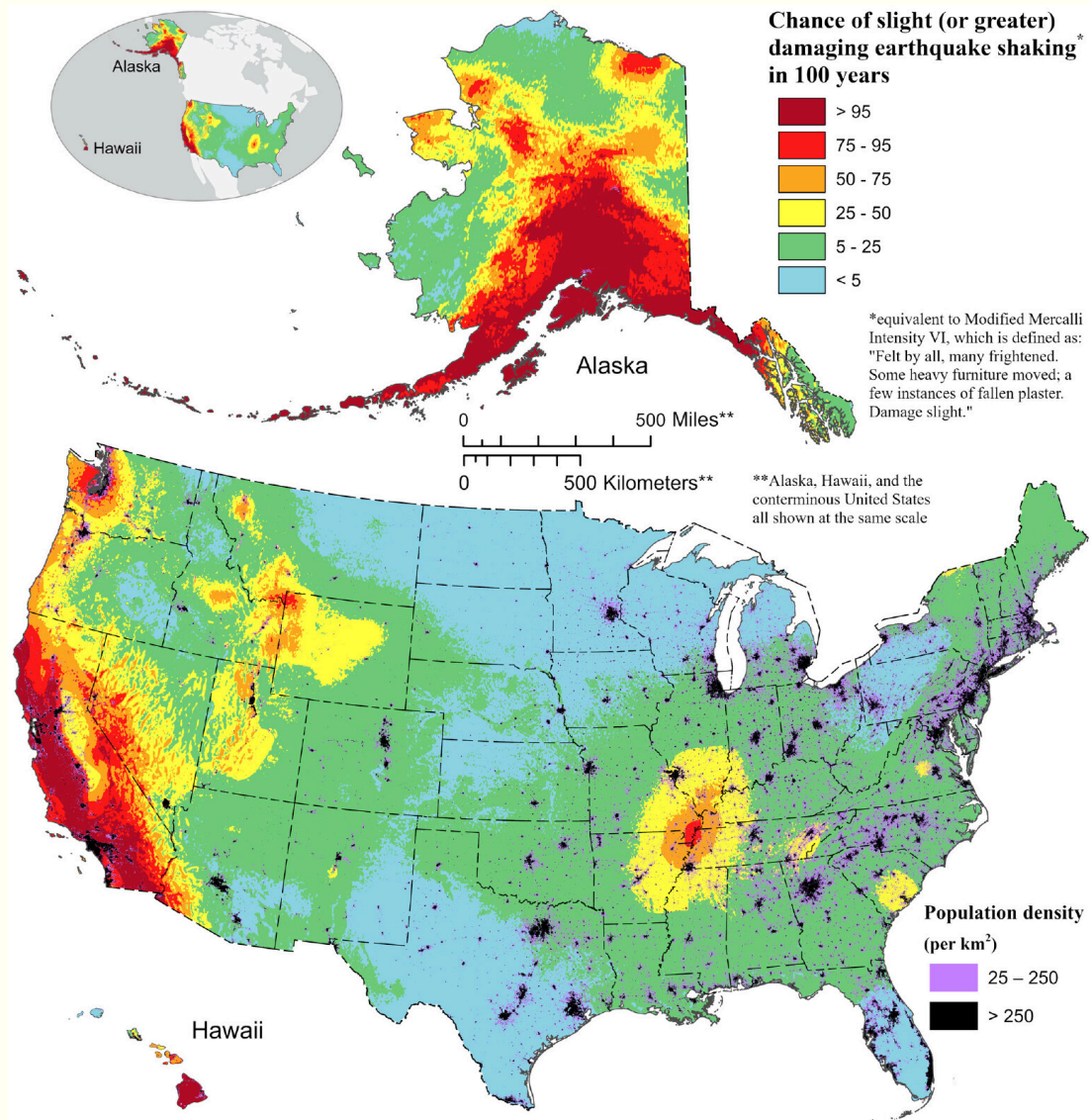


Figure 9.1 – National Seismic Hazard Model (2023). Map displays the likelihood of damaging earthquake shaking in the United States over the next 100 years. Image credit: [USGS](#), Public Domain.

a. Explain what the colors on Figure 9.1 mean.

b. Which parts of the U.S. have a high earthquake hazard?

c. Which parts of the U.S. have a low earthquake hazard?

- d. Why are earthquake hazards high on the west coast of the U.S.?

- e. Do any locations of high earthquake-shaking hazards not correspond to any plate boundaries? Can you come up with an explanation for these areas?

- f. **Critical Thinking:** Will places on the map that have the same color have the same level of damage if an earthquake occurs?

Exercise 9.2 – Comparing Earthquakes at Divergent Plate Boundaries

Divergent plate boundaries occur in both oceanic and continental crust. In oceanic plate boundaries (mid-ocean ridges), numerous transform faults offset these ridges. The location of earthquakes along these divergent boundaries is controlled by whether or not the divergent boundary and/or transform breaks due to brittle deformation. The brittle behavior of rocks is partly a function of temperature and pressure. Typically, only shallow and cool rocks will break. So, you can look at the patterns of earthquakes to determine if a mid-ocean ridge is hot or cool. Why is this important? Well, life and mineral resources are both sensitive to the thermal conditions at ridge crests.

- a. Look at the patterns of the earthquakes for four different divergent zones (Figure 9.2). Describe the earthquake distributions in the oceanic (A-C) and continental rifts.

- a. Oceanic

- b. Continental

- b. For images A-C, are most earthquakes located on the spreading ridges, transforms, or both? Also, note if there are earthquakes located off the spreading ridge. Describe where the earthquakes are in images A-C.

- c. Is there a relationship between the spreading rate and earthquake distribution? Discuss this as a class to explain what you observe.

- d. An important feature of mid-ocean ridges is black smokers (hydrothermal vents). These form near or on spreading ridges in response to the thermal structure of a ridge, sea water interaction, and fracturing. They are sites for both mineral deposition and deep sea life. Which of these spreading ridges would you predict to have more black smokers? Why?

- e. Look at the distribution of earthquakes and volcanos in the East African rift zone. Do these occur in the same region? Explain your observations.

- f. Continental rifts occur in thick continental crust that is hard to break. Would you predict that there would be deeper earthquakes in continental rift zones? Do your observations support or disprove your hypothesis?

- g. **Critical Thinking:** The East African rift valley is home to most of the African large mammals as well as where hominid evolution began. What features of this rift are important for biologic and evolutionary activity?

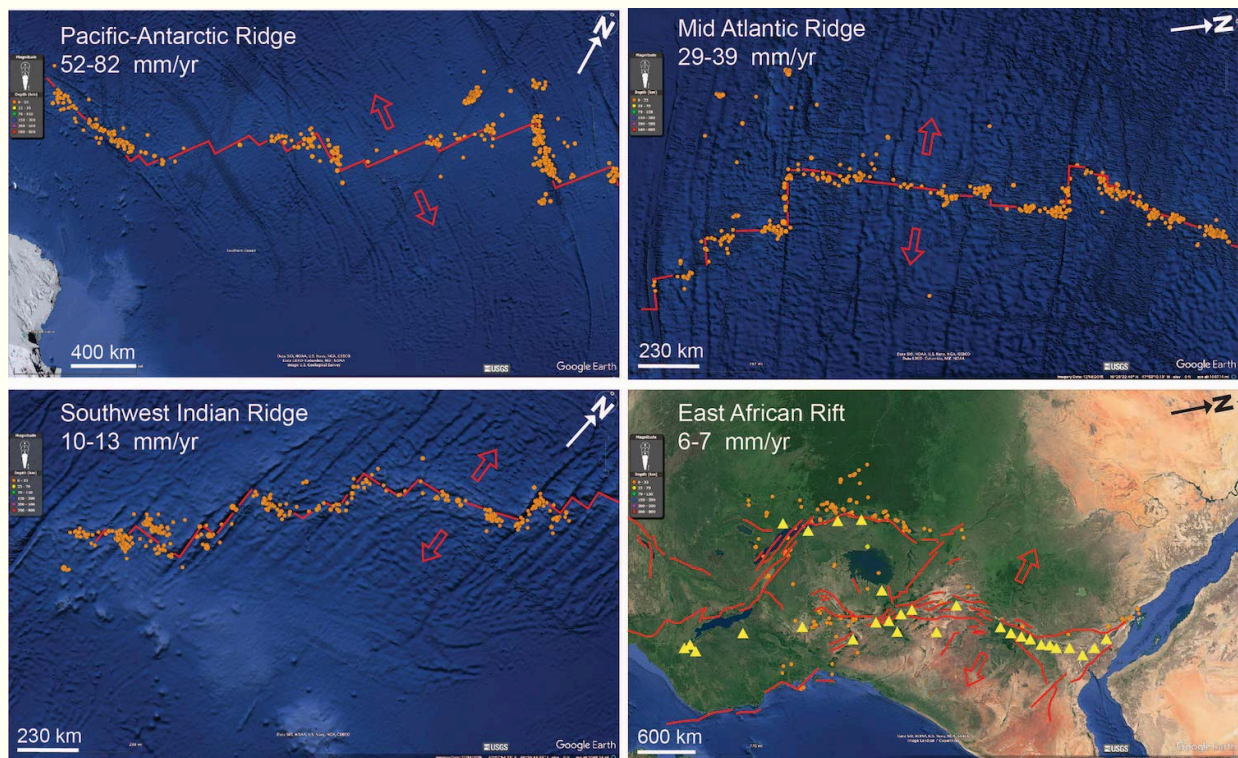


Figure 9.2 – Locations of earthquakes of magnitude greater than 4.5 for three oceanic rifts and one continental rift for a ten-year period from 2012–2022. Note that each map has been rotated so that the rift boundary is parallel to the long edge of the map. Maps A – C represent three different oceanic spreading ridges with fast to slow spreading rates derived from [Bird et al. \(2008\)](#). Map D shows the East African Rift. Red lines on all images are faults and ridge crest locations. For the continental rift, recent faults (red lines) and active volcanoes (yellow triangles) are from [Chorowicz \(2005\)](#). The orange dots indicate earthquakes originating at shallow depths of less than 33 km. The size of the dot is proportional to the magnitude of the earthquake. Image credit: Virginia Sisson CC BY-NC-SA. Base maps from Google Earth with epicenters generated using the U.S. Geological Survey Earthquake locator website, [Search Earthquake Catalog](#).

9.2 Seismic Waves

As you can imagine, technology does not exist to travel into all of Earth's layers. Geoscientists learn a great deal about Earth's structure through seismic waves. Seismic waves are vibrations in the Earth that transmit energy and occur during earthquakes, volcanic eruptions, and even man-made explosions and nuclear blasts.

Exercise 9.3 – Analogs for Seismic Wave Motion

When an earthquake occurs, seismic waves are released outward from the hypocenter (the location inside the Earth where the earthquake occurred). These waves have different characteristics, including their motion and velocity.

- a. Using a slinky (can be either metal or plastic), hold one end and have a partner hold the other. Stretch the slinky to at least 8". If you have a super slinky, you can go even further. Quickly push the slinky forward on your end and immediately pull back. Describe what happens.

- b. With the same setup, quickly move your end of the slinky up, down, and back to the middle. Describe what you see.

- c. Discuss with your instructor what these models represent.

- d. If you shorten or lengthen the slinky, what is the result?

- e. Does it make a difference if the slinky is metal or plastic? Why? _____

- f. Seismologists like to know the relationship between wavelength, frequency and amplitude of waves. Set up an experiment to demonstrate these with your slinky or with several slinkies.

You can picture seismic waves moving through the Earth as circular waves similar to what happens when a stone is thrown into a pond, but more complex. Seismic waves can be distinguished by a number of properties including the speed the waves travel, the direction that the waves move particles as they pass by, and where they don't propagate. In the previous exercise with a slinky, could you measure the wave speed? Typical seismic wave speeds are 330 m/s in air, 1450 m/s in water and about 5000 m/s in granite. The precise speed that a seismic wave travels through the Earth depends on several factors, most important is the composition of the rock.

Exercise 9.4 – Seismic Wave Velocity

When an earthquake occurs, seismic waves are released outward from the hypocenter (the location inside the earth where the earthquake occurred). These waves have different characteristics, including their motion and velocity.

- a. Imagine two cars on a highway are driving right next to each other. Car 1 is traveling at 60 mph, and Car 2 is traveling at 70 mph. Both will maintain their speed. How far apart are the cars after 1 hour?

- b. After 2 hours? _____
- c. After 5 hours? _____
- d. How many hours must pass for the cars to be 100 miles apart? _____
- e. If the time is 5:30 p.m. and the cars are 75 miles apart, at what time did they start moving?

- f. Seismic waves work the same way. P-waves and S-waves travel at different velocities away from the earthquake focus (Figure 9.3). Which wave travels faster? _____
- g. How long does it take a P-wave to travel 1,000 km? _____
- h. How long does it take an S-wave to travel 1,000 km? _____
- i. You can use the difference in travel time to determine how far away an earthquake occurred. If the travel time difference between a P-wave and S-wave is 1 minute, how far away was the earthquake?

- j. **Critical Thinking:** Does this tell you the exact location of the earthquake? Why or why not?

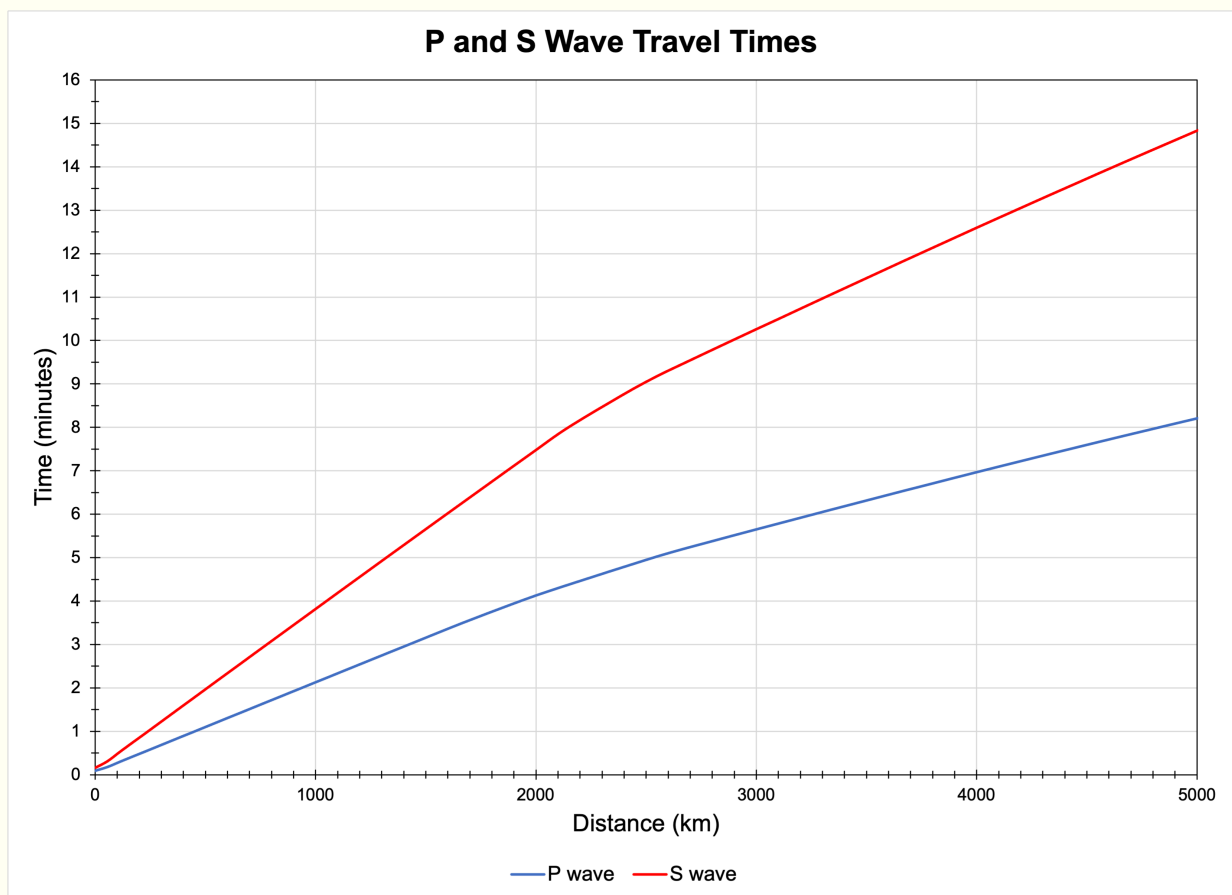


Figure 9.3 – P and S wave travel times as a function of source distance for an earthquake. [Data from the USGS](#)

The measurement for how powerful an earthquake is is called its magnitude. The magnitude can vary from place to place based on distance, type of surface material, and other factors. You may have heard

about the Richter scale (M_R) for measuring magnitude, which is based on the amplitude of the seismic waves, but in practice it's not commonly used anymore. The Moment Magnitude (M_W) is more accurate, especially with more power earthquakes. It's based on the strength of the rock along the fault, the area of the fault that slipped, and the distance the fault moved. Thus, stronger rock material, or a larger area, or more movement in an earthquake will all contribute to produce a larger magnitude.

9.3 Locating Earthquakes

Since earthquakes all over the world, how do we determine where they occur? Sometimes they occur in the middle of the ocean or in remote areas where no one lives. Is this like the age old question that if a tree falls in the woods, does it make a sound? Even if there's no person or other animal around to hear the tree falling and crashing, a recorder with a microphone could certainly record those vibrations—as sound. The same is true for earthquakes. Geoscientists have set up earthquake monitoring stations using [seismometers around the world](#) to record earthquake waves. These are set-up on global, national and regional scales. For example, the San Francisco Bay region has over 550 local monitoring stations while the Global Seismographic Network only has 152.

Do you want to set up your own earthquake monitoring station? You can with your smart phone as these have motion sensors to determine whether your phone is stationary or falling out of your hand. These include Seismograph, iSeismo, and VibrationMeter. In addition, there are now apps to help alert you if you live in an earthquake prone area, such as MyShake and Earthquake.

Exercise 9.5 – Locating an Earthquake

The location of earthquakes can be found by triangulating the origin of seismic waves. Figures 9.4 – 9.6 contain three-component seismograms for three different locations. The three components represent different directions of motion: Up-Down (vertical), North-South, and East-West.

- On Figures, mark the arrival of the first P waves, S waves, and surface waves.
- Determine the arrival times of P and S waves at each station (Figures 9.3 – 9.5). Be as exact as possible and record the times in Table 9.1.

Table 9.1 – Seismic wave data to locate an earthquake

Seismic Station Location	P wave arrival time	S wave arrival time	S-P time (mm:ss)	Distance (km)
Tuscon, AZ				
Corvallis, OR				
Cathedral Caves, MO				

- Determine the amount of time between the arrival of P and S waves at each station. Record the time difference in Table 9.1.
- Now that you know the difference in arrival times, you can tell how far away the earthquake was from each station. Use Figure 9.3 and find the chunk of time between the two curves. Record the distance in Table 9.1.
- Now, you're going to triangulate the location of the earthquake. You can do this one of two ways:
 - Head to the [Iris triangulation webpage](#). Click "+ Station" and input the latitude and longitude of

each station and the distance of the epicenter you determined. Look at the bottom of the page to edit this data. This will create a colored circle around each station that has a radius equal to the distance you entered. If you select this, show your instructor the map you made on the Iris web-page, then mark the earthquake's epicenter on Figure 9.7.

2. Plot the three circles of your measured distance for each station using a compass on Figure 9.7. For both ways, where the three circles intersect (or come close to intersecting) is the location of the earthquake.

- f. Is this earthquake located near a plate boundary? If so, what type of plate boundary is nearby?

- g. How could you determine a more precise location?

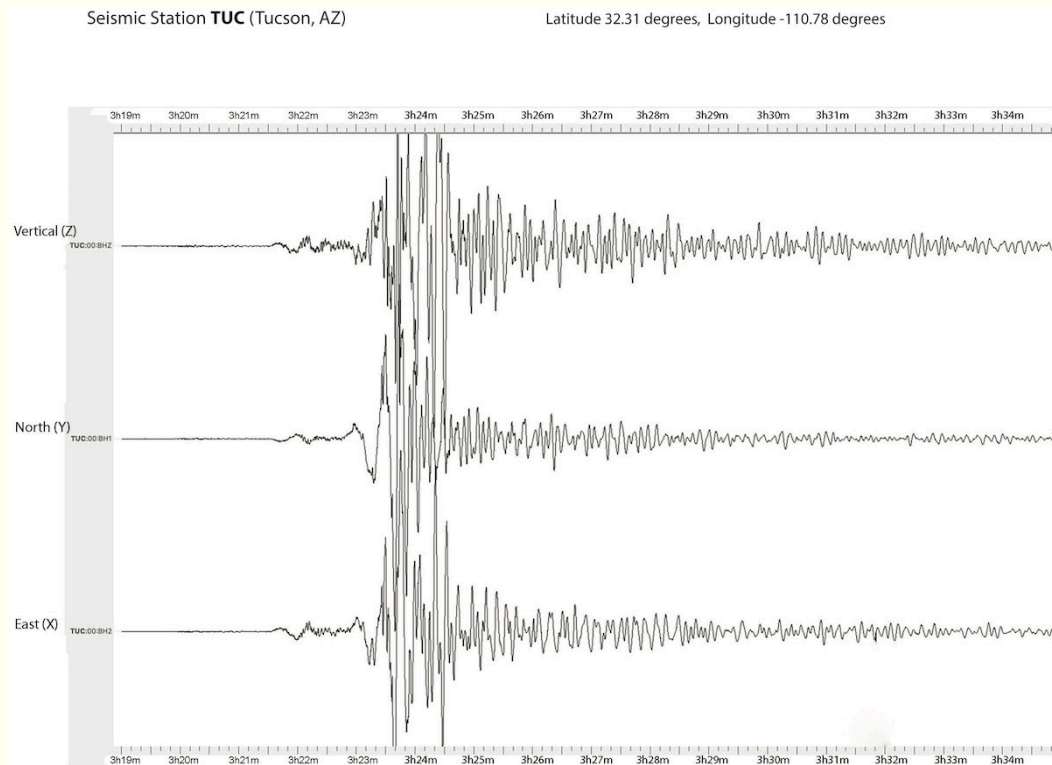


Figure 9.4 – Seismogram from the Tucson, AZ station for an earthquake that occurred on July 6, 2019.
Image Credit: [EarthScope Consortium](#), CC BY.

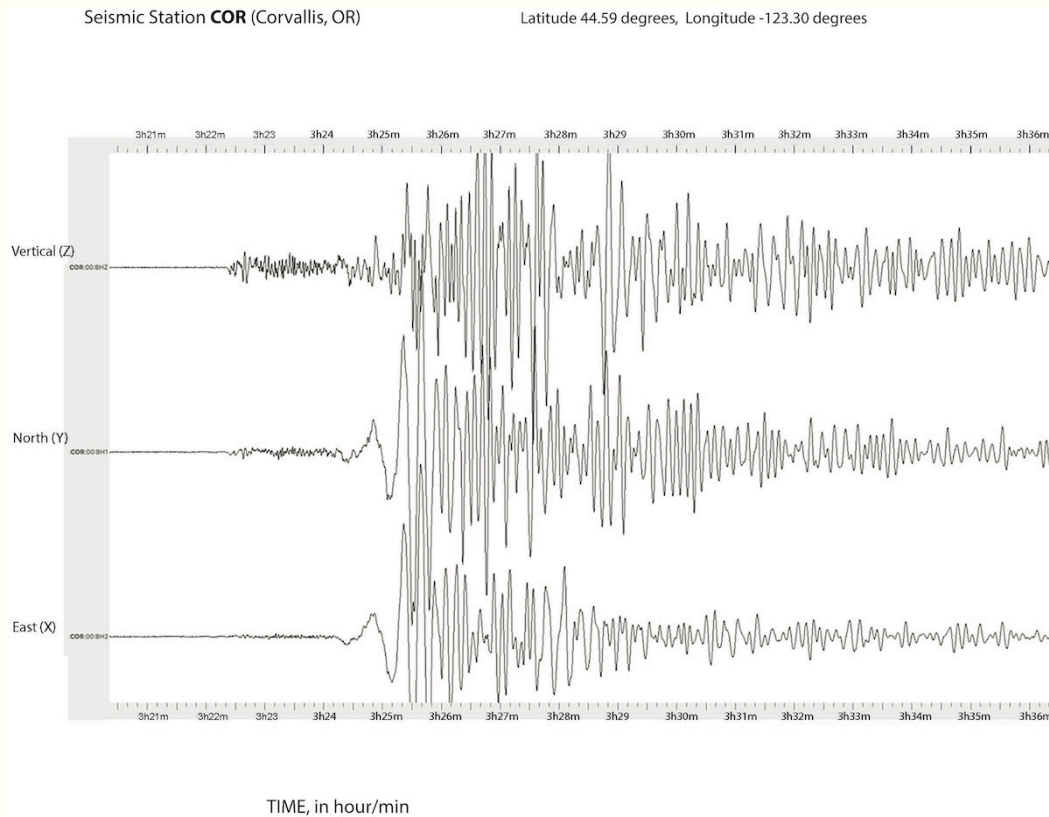


Figure 9.5 – Seismogram from the Corvallis, OR station for an earthquake that occurred on July 6, 2019.
Image Credit: [EarthScope Consortium](#), CC BY.

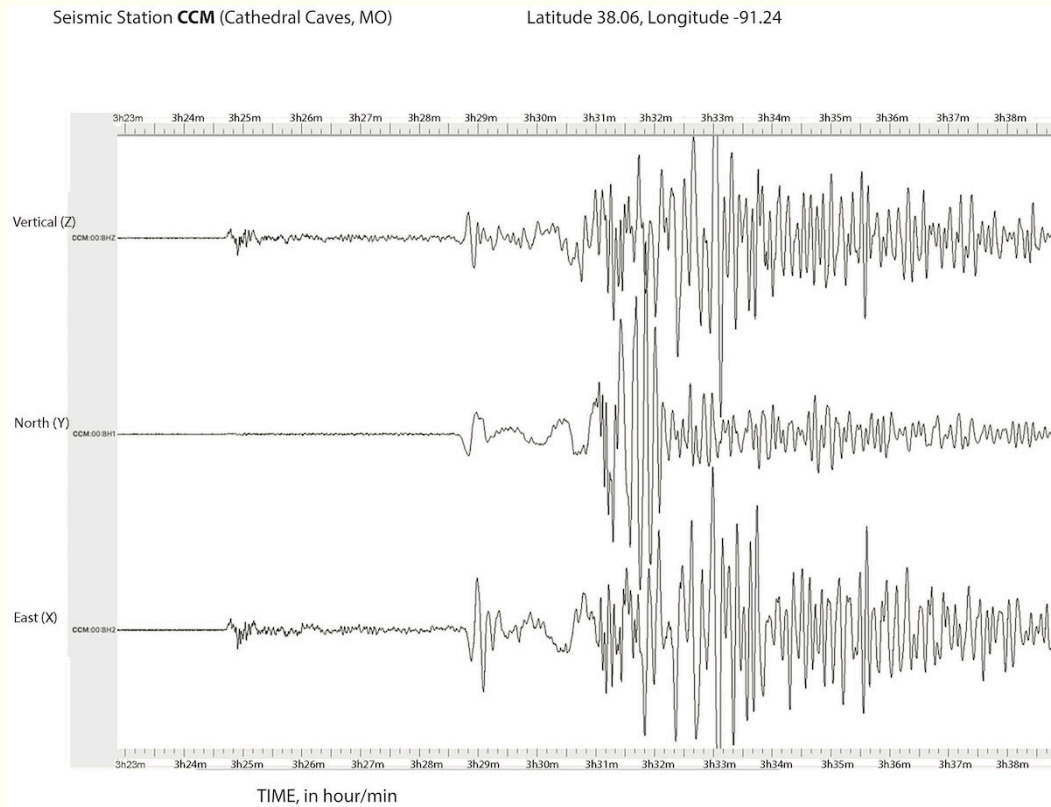


Figure 9.6 – Seismogram from the Cathedral Caves, MO station for an earthquake that occurred on July 6, 2019. Image Credit: [EarthScope Consortium](#), CC BY.



Figure 9.7 – Map of North America for plotting the earthquake epicenter. The orange triangles are the seismograph station locations: Corvallis, OR; Tuscon, AZ; and Cathedral Cave, MO. Image Credit: Daniel Hauptvogel, CC BY-NC-SA.

This exercise is adapted from [IRIS/SAGE](#).

9.4 Induced Seismicity

Induced seismicity is typically earthquakes and tremors that are caused by human activity that alters the stresses and strains on Earth's crust. The first case of induced seismicity occurred in 1932 in Algeria's Oued Fodda Dam. Most induced seismicity is of a low magnitude. **Injecting fluid** underground can induce earthquakes, a fact that was established decades ago. Injection increases the fluid pressure within the Earth, creating an area more likely to fail in an earthquake. When injected with fluids, even faults that have not moved in historical times can be made to slip and cause an earthquake.

Why inject fluid underground? Several reasons are wastewater disposal, hydraulic fracturing and enhanced oil recovery. Within the United States, each of these activities has induced earthquakes in the past few years. These are regulated under the [Safe Drinking Water Act](#) with standards set by the U.S. Environmental Protection Agency. Other purposes for injecting fluid underground include enhanced geothermal systems and geologic carbon sequestration.

Exercise 9.6 – Fracking and Earthquakes

Since 2001, oil and gas have been extracted from shale, but shale is not a permeable rock, so fluids can't pass through it. Geologists can increase the permeability of shale so that oil and gas can flow and be extracted. This is done by hydraulic fracturing ("fracking"). During fracking, fluids are pumped into a well at high pressure to open and widen cracks in the shale, allowing the oil and gas to flow easier. This process causes small earthquakes (magnitudes smaller than 1), but large ones do occur with the largest induced earthquake being a M4 in Texas.

In addition, wastewater (a by-product of fracking) is frequently disposed of by injection into deep wells. The injection of wastewater into the subsurface can also cause earthquakes that are large enough to be damaging. Wastewater is injected deep underground, far below groundwater or drinking water aquifers. The largest earthquake known to be induced by wastewater disposal was a M5.8 earthquake that occurred near Pawnee, Oklahoma, in 2016.

Both fracking and wastewater disposal processes have affected Texas, Oklahoma, and New Mexico. Figure 9.8 shows the distribution of all earthquakes for two five-year periods 1997-2001 and 2019-2023, and Figure 9.8 shows the frequency of earthquake magnitude from 2019-2023.

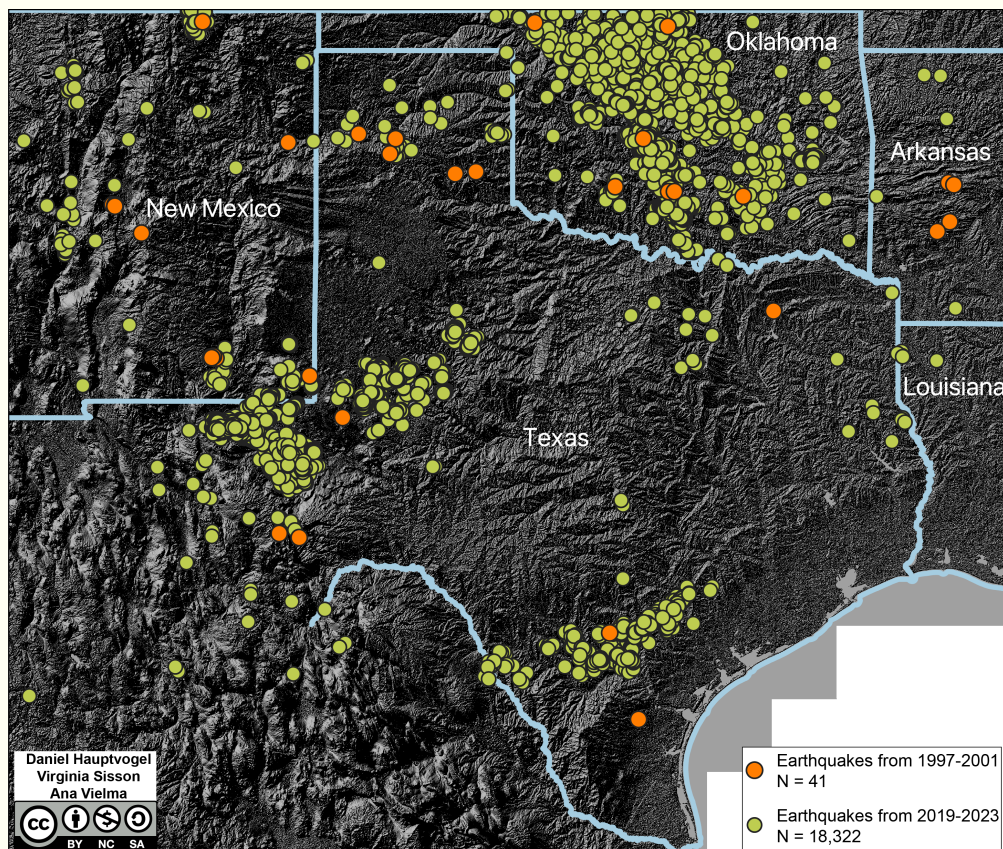


Figure 9.8 – Hillshade digital elevation model showing locations of earthquakes greater than 1.5 magnitude for Texas, Oklahoma, New Mexico, and part of northern Mexico. Orange circles are earthquake epicenters from 1997-2001, and green circles are earthquake epicenters from 2019-2023. There is significant overlap of green circles. Earthquake data the [U.S. Geological Survey](#). Image credit: Daniel Hauptvogel, Virginia Sisson, and Ana Vielma, CC BY-NC-SA.

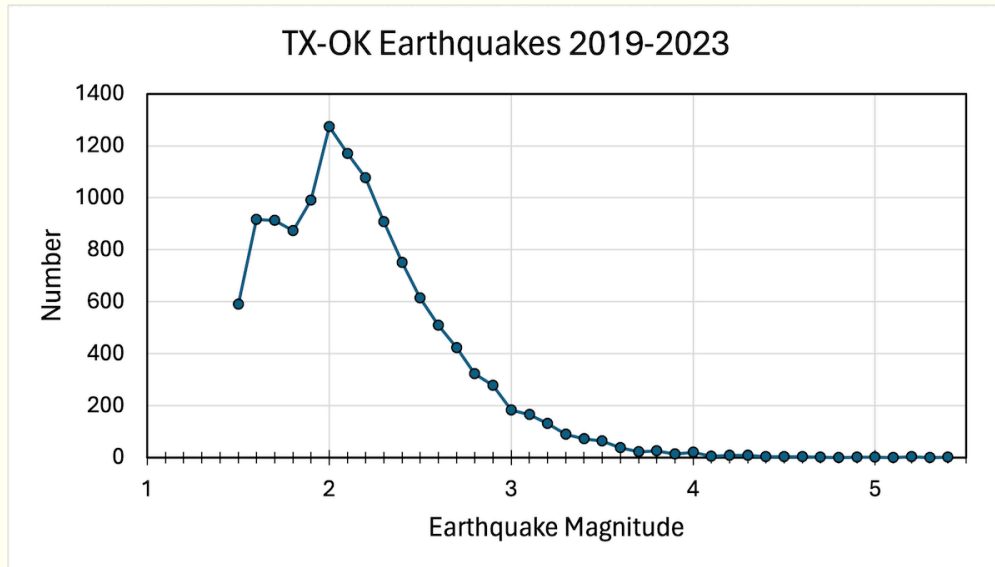


Figure 9.9 – Distribution of earthquake magnitude from 2019-2023. Earthquake data is from the [U.S. Geological Survey](#). Image credit: Daniel Hauptvogel, CC BY-NC-SA.

- a. Use the 1997-2001 data from Figure 9.8 to determine the natural seismicity and where it occurred in this region. Do the earthquakes cluster in distinct areas? If so, where are these located?

- b. Look at Texas in Figure 9.8, are the orange-colored earthquakes associated with any specific rocks? Open the [interactive map of the geology of Texas](#) and look at the regional trends and rock types; look to see what type of sedimentary rocks are there.

- c. Use the 2019-2023 data from Figure 9.8 to understand where induced seismicity occurred in this region. Do the earthquakes cluster in distinct areas? If so, where are these located?

- d. Do you think there are any natural earthquakes in in the 2019-2023 data?

- e. Look at Texas in Figure 9.8, are the clusters of green-colored earthquakes associated with any specific rocks? Open the [interactive map of the geology of Texas](#) and look at the regional trends and rock types;

look to see what type of sedimentary rocks are there.

- f. Are these induced earthquakes hazardous? You can start to feel earthquakes with a magnitude of about 2.5, and you generally need above magnitude 4 to see damage, especially to poorly constructed buildings. Use Figure 9.9 to determine if there are any damaging earthquakes from 2019-2023.

- g. **Critical Thinking:** Do you think that building codes in these regions with high induced seismicity need to be changed?

9.5 Earthquake Hazards

Many movies and news reports depict death and destruction caused by earthquakes. Some of the natural hazards are landslides, fissures, avalanches, and tsunamis. Most of the hazards to people come from man-made structures themselves and the shaking they receive from the earthquake. The real dangers to people are being crushed in a collapsing building, drowning in a flood caused by a broken dam or levee, getting buried under a landslide, or being burned in a fire. In order to reduce risk in populated area as well as develop policies for land-use, insurance needs, and earthquake resistant design, knowledge of the types of hazards in any area need to be mapped. Some of these hazards are related to the types of rocks as well as how steep the terrain is. In the next exercise you will integrate information from a hazards map, geologic map as well as satellite image showing topography.

Exercise 9.7 – Earthquake Hazards

There are many other earthquake hazards besides the shaking from seismic waves. Liquefaction and landslides are two common hazards. Liquefaction occurs when loose, water-logged sediment loses its strength due to intense shaking from earthquakes, basically turning into quicksand. A landslide is a mass of earth or rock sliding down a mountain or cliff. Figure 9.10 is a map of the San Francisco Bay area in California that shows these hazards.

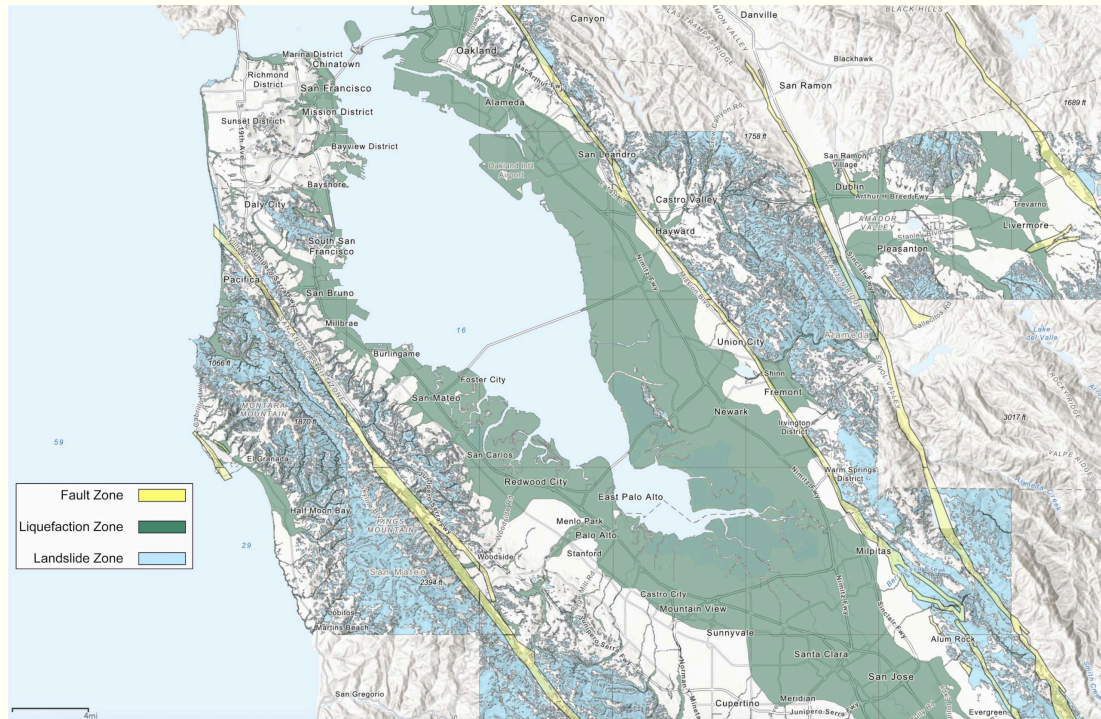


Figure 9.10 – Liquefaction and landslide hazard map of the San Francisco Bay area. Yellow are the locations of fault zones, green are liquefaction zones, and blue are landslide zones. Data is not available for all areas, which is why colored zones abruptly stop. The background is a shaded digital elevation model. Image Credit: adapted from the [California Department of Conservation](#), Public Domain.

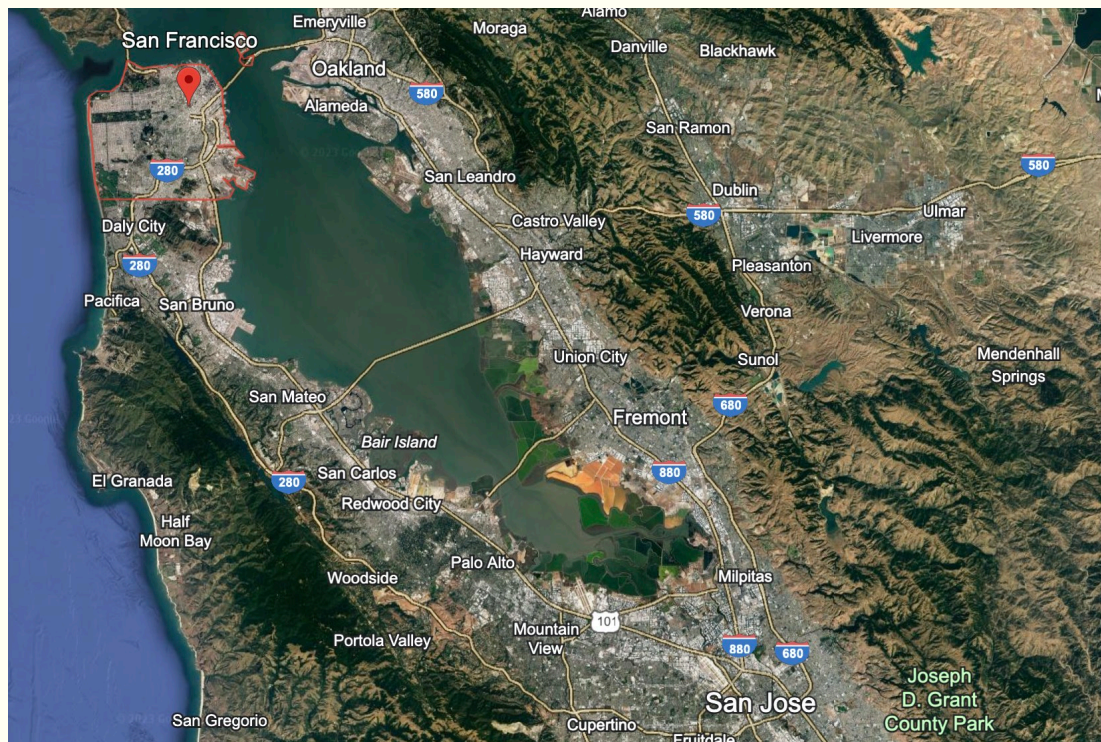


Figure 9.11 – Google Earth image of the San Francisco Bay region. This covers the same region as Figure 9.10.

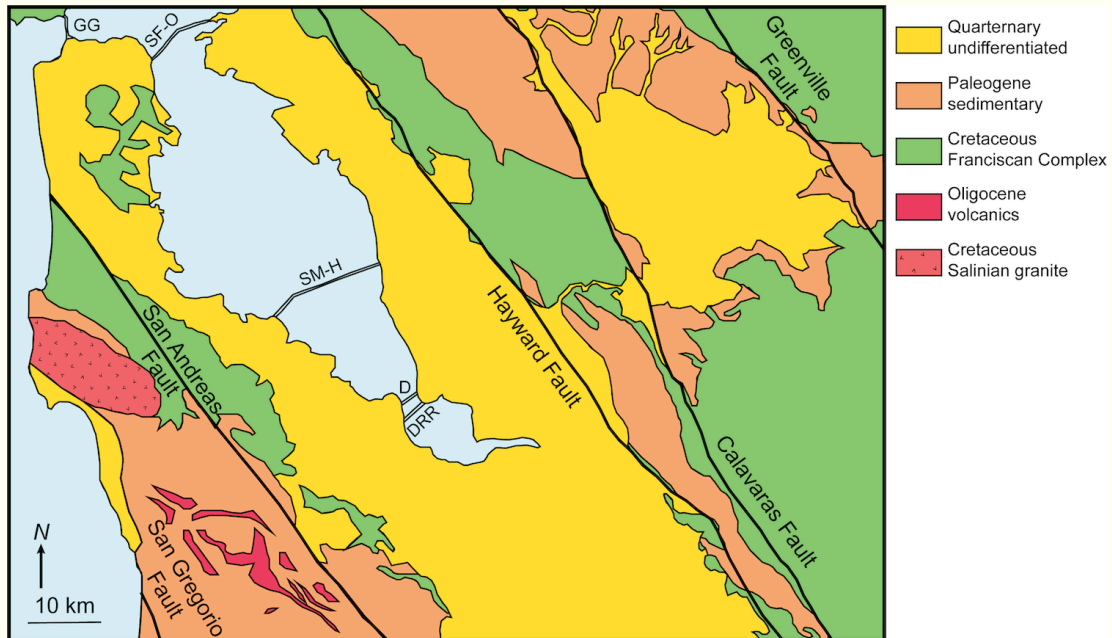


Figure 9.12 – Simplified geologic map of the San Francisco Bay region. Quaternary deposits include artificial fill, mud deposits, alluvium, among other deposits. Sedimentary rocks include Pliocene to Eocene units. The Franciscan Complex has sedimentary rocks, volcanics, and metamorphic rocks including serpentinite. There are also two igneous units: Oligocene volcanics (red) and Cretaceous Salinian granite (red with pattern). Also, shown are bridges across San Francisco Bay including the Golden Gate bridge (GG), San Francisco-Oakland Bay bridge (SR-O), Dumbarton (D) and Dumbarton Railroad bridge (DRR). Image credit: Virginia Sisson CC BY-NC-SA adapted from Graymer et al. (2006)

a. What areas are prone to liquefaction?

b. What areas are prone to landslides?

c. Compare the Google Earth image (Figure 9.11) and the geologic map (Figure 9.12) to the hazards map (Figure 9.10). Describe some of the relationships between the type of hazard, geologic units, and topography for liquefaction and landslides.

d. Choose one of the bridges across San Francisco Bay and determine the geologic hazards associated with both sides of the bridge.

e. Your best friend is getting a job in San Ramon CA as a geologist in the headquarters of Chevron. She

knows that earthquake hazards abound in CA. The hazard map, however, doesn't indicate the hazards in this region located on the NE of Figure 9.10. Using the topography and geologic maps (Figures 9.11 and 9.12), let her know what the potential hazards are and where they occur around San Ramon CA.

- f. Use outside resources to discover some of the historical damage from earthquakes in this region. Which type of hazard was most damaging for these earthquakes? Each group should do one earthquake event and share your results with the class. Some of the events include:

- i. 1906 M7.9 San Francisco earthquake _____
- ii. 1911 M6.0 Calaveras fault Morgan Hill earthquake _____
- iii. 1980 M6.0 Livermore earthquake _____
- iv. 1984 M6.3 Calaveras fault Morgan Hill earthquake _____
- v. 1989 M7.1 Loma Prieta earthquake _____
- vi. 2001 M5.1 Napa earthquake _____
- vii. 2007 M5.7 Calaveras fault _____

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson, and Kaitlin Thomas

CHAPTER 10: DEFORMATION AND STRUCTURES

Brittle and Ductile

Learning Objectives

The goals of this chapter are to:

- Understand geologic deformation and structures
- Interpret brittle and ductile structures
- Evaluate three dimensions of deformation

10.1 Deformation

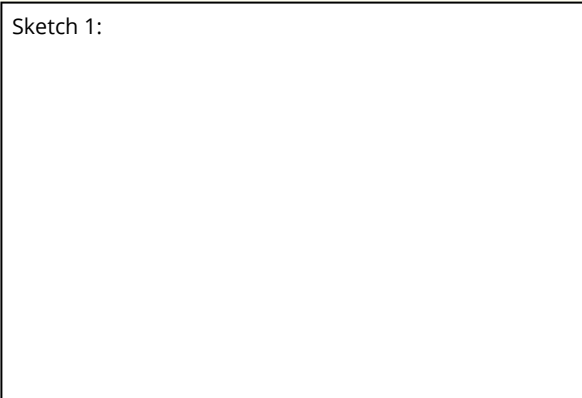
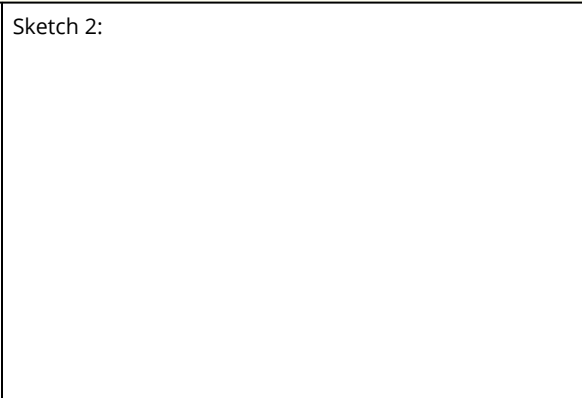
The deformation of rock layers can make interpreting the geologic history of those layers more difficult. However, it can also tell us about the tectonic processes that may have occurred in the region. For these reasons, geologists must understand how deformation of rock layers occurs and how to deconstruct the often confusing structures that result from deformation. Then, the original position of the rock layers can be determined. Remember that these tectonic processes can occur on vastly different spatial-temporal scales and can vary based on the type and thickness of rocks that are being deformed, so no two faults or folds will be exactly alike.

Exercise 10.1 – Observing Deformation

Your instructor has placed a block model on your table.

- Create sketches of the block model from at least two different viewpoints.

Table 10.1 – Block sketches

Sketch 1:	Sketch 2:
	

b. Describe what you think is significant about your block model.

To identify different types of deformation, you first need to be able to recognize **bedding** and foliation planes (layers). Look for distinct changes in color, breaks between layers or **foliation**, changes in **lithology**, etc. When you look at an **outcrop**, first try to identify the bedding or foliation. This may be horizontal or tilted. Folded, tilted, faulted bedding and foliation planes are useful markers that allow you to investigate deformation structures in rocks. They can be continuous and followed for long distances or shorter if the depositional environment has local changes.

You can identify deformational features by tracing these bedding and foliation planes. Only two dimensions are often visible, and you need to infer the third dimension. So, look at the outcrop and note if the bedding/foliation planes are straight or curved. If they are curved, the rocks deformed by bending or flowing (**ductile**) and are folded. If they are straight, then you are looking at **brittle** deformation. What controls brittle (breaking) versus ductile (bending) are complex interactions between temperature and rock types. Remember how deep you observed earthquakes occurring? Earthquakes are brittle deformation and occur at shallow depths and low temperatures. As temperature increases, the rocks switch to ductile deformation, and there are no more earthquakes.

Figure 10.1 shows how rock type controls whether the rocks bend or break. The shales bend, whereas the sandstone breaks. Are the bedding planes discontinuous across a break in the rocks? If they are discontinuous, this typically indicates a brittle fault. In this case, follow a few bedding planes, and if they are continuous, you are seeing folds and ductile deformation.

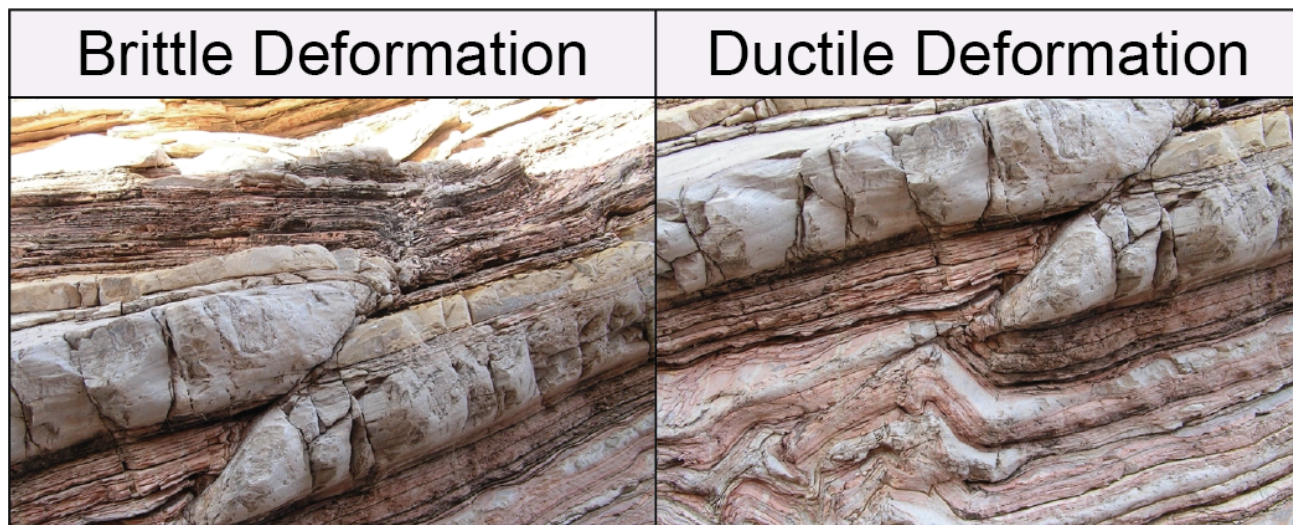


Figure 10.1 – Brittle and ductile deformation. The grey limestone fractures in a brittle fashion [left], and the reddish mudstone (shale) deforms in a more-plastic fashion [right]. These are along the same normal fault in the Cretaceous Boquillas Formation, Ernst Tinaja Canyon, Big Bend National Park, TX. Image credit: Alexander Robinson CC BY.

10.2 Ductile Deformation

Folds form when layers or beds are bent or folded due to convergent plate tectonics. They can be

rounded or angular. The plane that marks the center of the fold is called the **axial plane**. The line that marks where the axial plane intersects the surface of Earth is called the **hinge line**. The areas on either side of the curved hinge zone stick out like arms or legs and are appropriately called **limbs**. There are often several folds connected (see Figure 10.2). If the bedding planes tilt down from the axial plane, this is an **anticline** (easy to remember since it sort of looks like an A). However, if the bedding planes tilt toward the axial plane, this is a **syncline** (Figure 10.1). Folds are common in convergent plate boundaries.

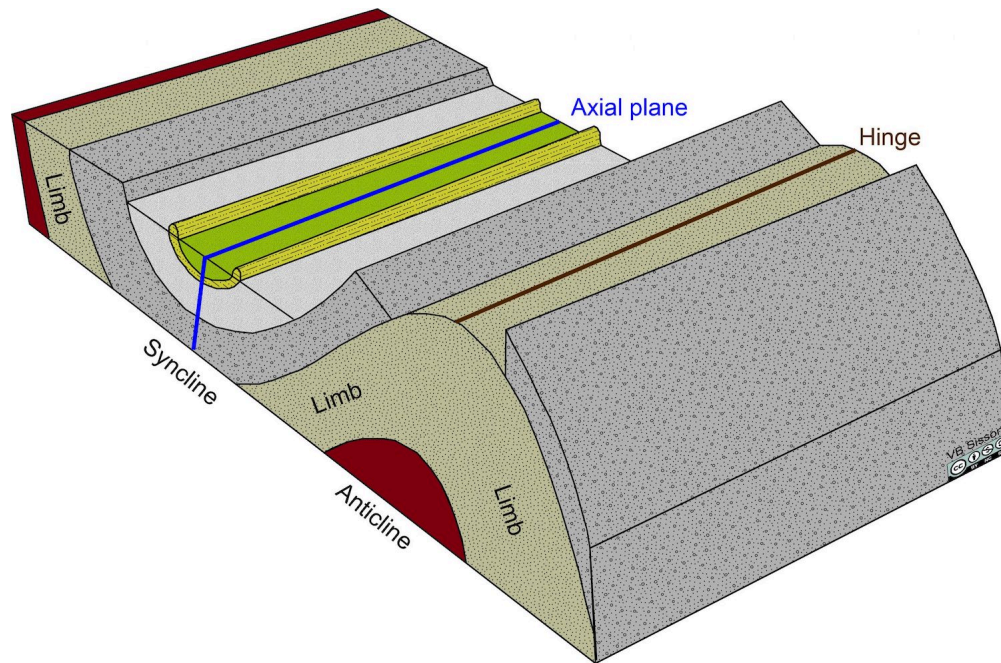


Figure 10.2 – Schematic folds with an anticline and syncline pair showing the fold limbs, axial plane, and hinge line. The layers are from oldest red, tan, dark gray, light gray, yellowish, and youngest is green. The top of the folds is eroded, showing the relative ages of the layers. Image credit: Virginia Sisson CC BY-NC-SA

Folds vary in size and shape. Some cover hundreds of kilometers in width, and others measure a few centimeters or less. Folds are generally classified according to the orientation of their axial plane, which can be vertical, horizontal, or inclined at any intermediate angle. In addition, the angle between the axial plane and the fold limbs is important for classifying folds. The angle of the axial plane relative to horizontal is called **plunge**. So, in addition to the folds shown 10.2, there are a variety of other folds shown in Figure 10.3. These include ductile folds:

- Symmetrical – vertical axial plane with the same dip for both fold limbs
- Asymmetrical – axial plane is tilted with a shallower dip on the left fold limb compared to the right fold limb
- Overturned – axial plane is tilted and the left limb has a shallow dip whereas the right limb with the stratigraphy overturned (upside down)
- Recumbent – horizontal axial plane with the same dip for both fold limbs

and brittle folds:

- Box – rectangular fold in which the fold limbs are right angles. This fold has three limbs
- Fault-bend – tilted axial plane and angular fold limbs. These form over **thrust faults** (see next exercise)
- Chevron – tilted to vertical axial planes with straight limbs that abruptly bend at one point at their

hinge zone.

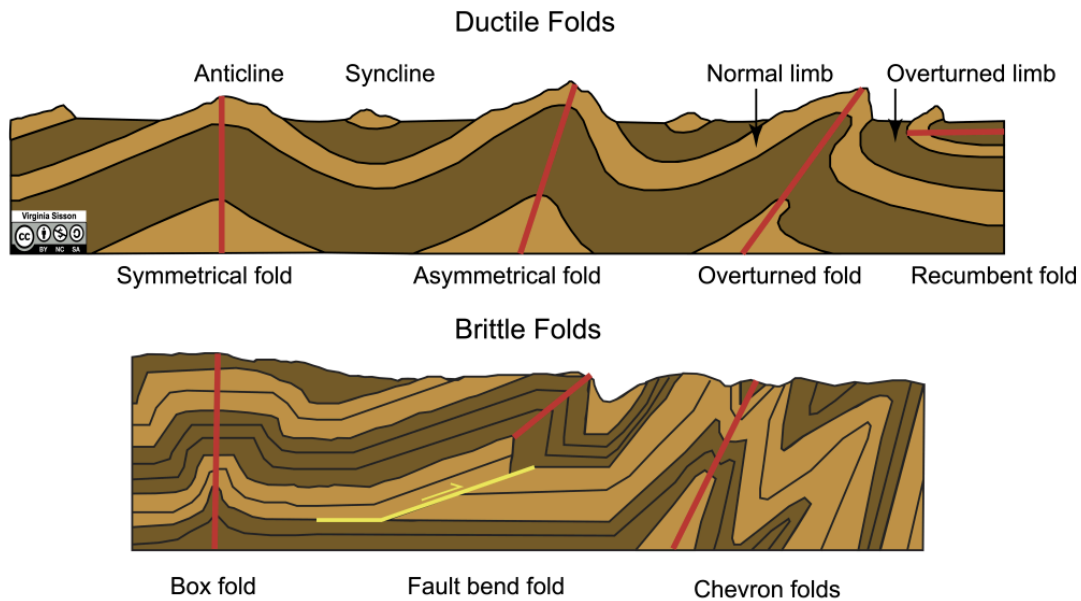


Figure 10.3 Schematic fold types. The thick red lines indicate the axial plane. The yellow line is a thrust fault with an arrow showing direction of movement. Note that the axial plane is noted in the anticlines except for the recumbent fold which is in a syncline. Image credit: Virginia Sisson CC BY-NC-SA.

Exercise 10.2 – Identifying Folds

Folds can be both brittle (bent) and ductile (rounded) features. Figure 10.4 shows six photos of folds. These start as large mountain scale folds (A and B) and get smaller and more complicated (C to F). There are geology rock hammers for scale in images C and D.

- For each photo, identify the type of fold shown and the direction of stress needed to create it. There is more than one fold in E and F.
- Sketch the axial plane(s).
- Indicate the age of the sedimentary units with “o” for oldest and “y” for youngest.
- Describe the characteristics of the folds by filling out Table 10.2. Some characteristics include what is the dip of the axial plane and are the dips of the layers similar on both sides of the fold, symmetry of fold (dip of each limb relative to axial plane), type of fold (anticline, syncline, inclined, recumbent, box, fault bend, etc.). Since folds form in convergent tectonic settings, you don't need to determine the tectonic setting for these features

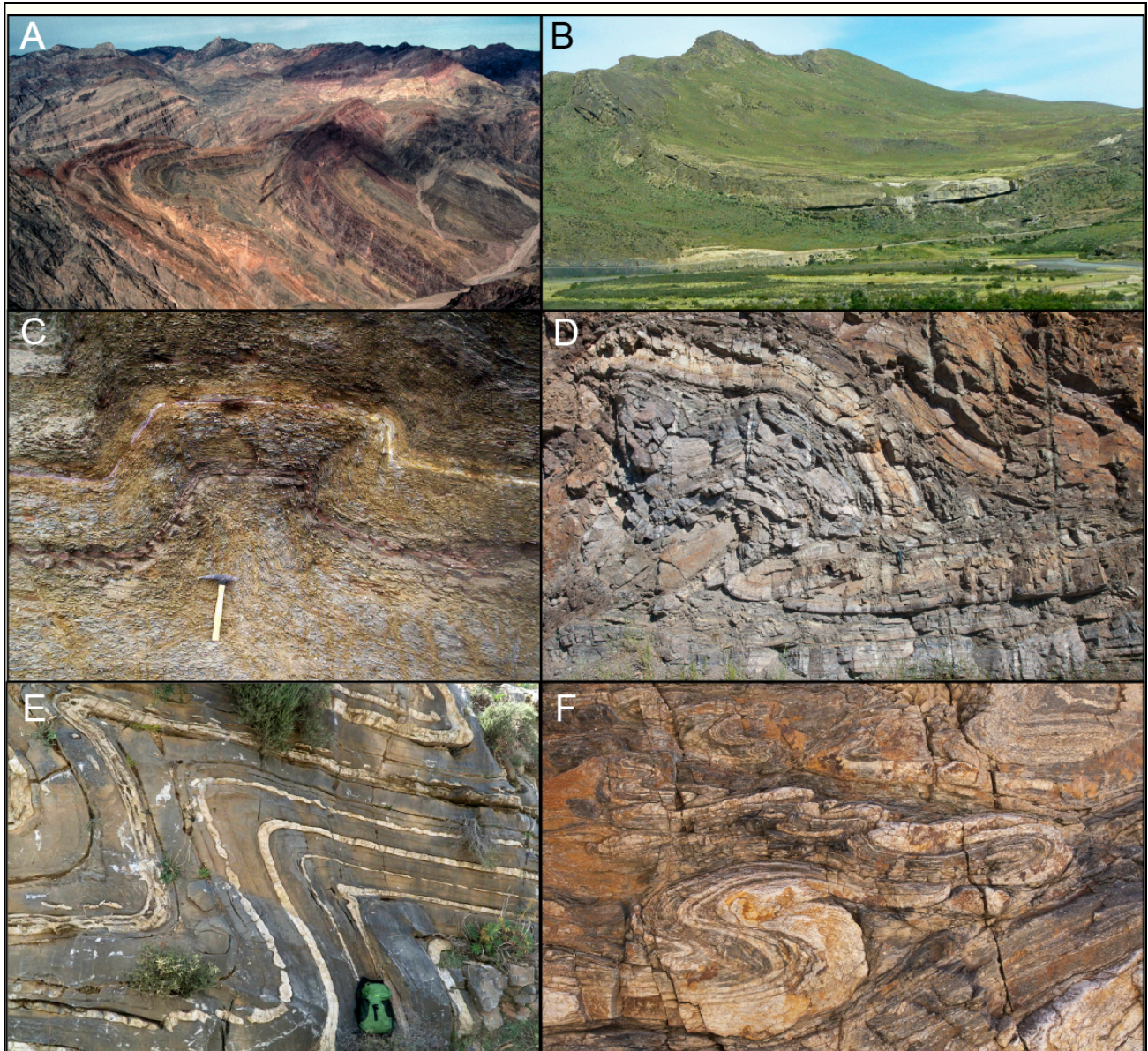


Figure 10.4 – Photos of ductile deformation. Locations are A. Death Valley CA; B. C. Morro Solar, Peru; D. British Columbia, Canada; E. Southern Peru; F. Death Valley CA. Image credit: A, D, E and F by Marli Miller, CC BY-NC-SA; B. by James St. John, CC BY; and C by Miguel Vera Leon CC BY.

Table 10.2 – Fold features and identification					
Photo #	Brittle or Ductile	Angle of Axial Plane	Axial Plane Curvature	Fold Symmetry	Type of Fold
A					
B					
C					
D					
E					
F					

10.3 Brittle Deformation

Let’s go over faults. First, ask yourself if you are looking at the Earth’s surface or a slice (cliff or outcrop along a road) through the Earth. Once you’ve done that, you will know if you are looking at either vertical (up and down) or horizontal (side to side) motion.

Vertical motion is called **dip-slip**. If the motion is mostly down, then this is a **normal fault**. If the motion is up, it is a **reverse** or **thrust fault**. The difficulty is deciding if the motion is up or down. To help with this, imagine standing with the fault above your head. Your feet are on a layer that doesn’t move. Some call this the **footwall**. The rocks above your head are called the **hanging wall**, as they might come crashing down on you. Then, do you have to look up or down to find this same layer on the other side of the fault (Figure 10.5)? The difference between a thrust and reverse fault is how steep the fault is. If the fault is shallow, this is a thrust fault. If it is steep, this is a reverse fault. Reverse faults are common in divergent tectonic settings, whereas thrust and reverse faults are common in convergent tectonic settings.

Horizontal motion is called **strike-slip** or transform; these are common in transform plate boundaries. If you have a vertical section through a strike-slip fault, one side will move toward you and the other away. From the top view, see if the features moved to the right or left. Imagine you’re on one side of the fault, standing on an object cut in half by the fault. Then, look across the fault and see if the other half of the object has moved to the left or right. It doesn’t matter which side of the fault you are on (see Figure 10.4).

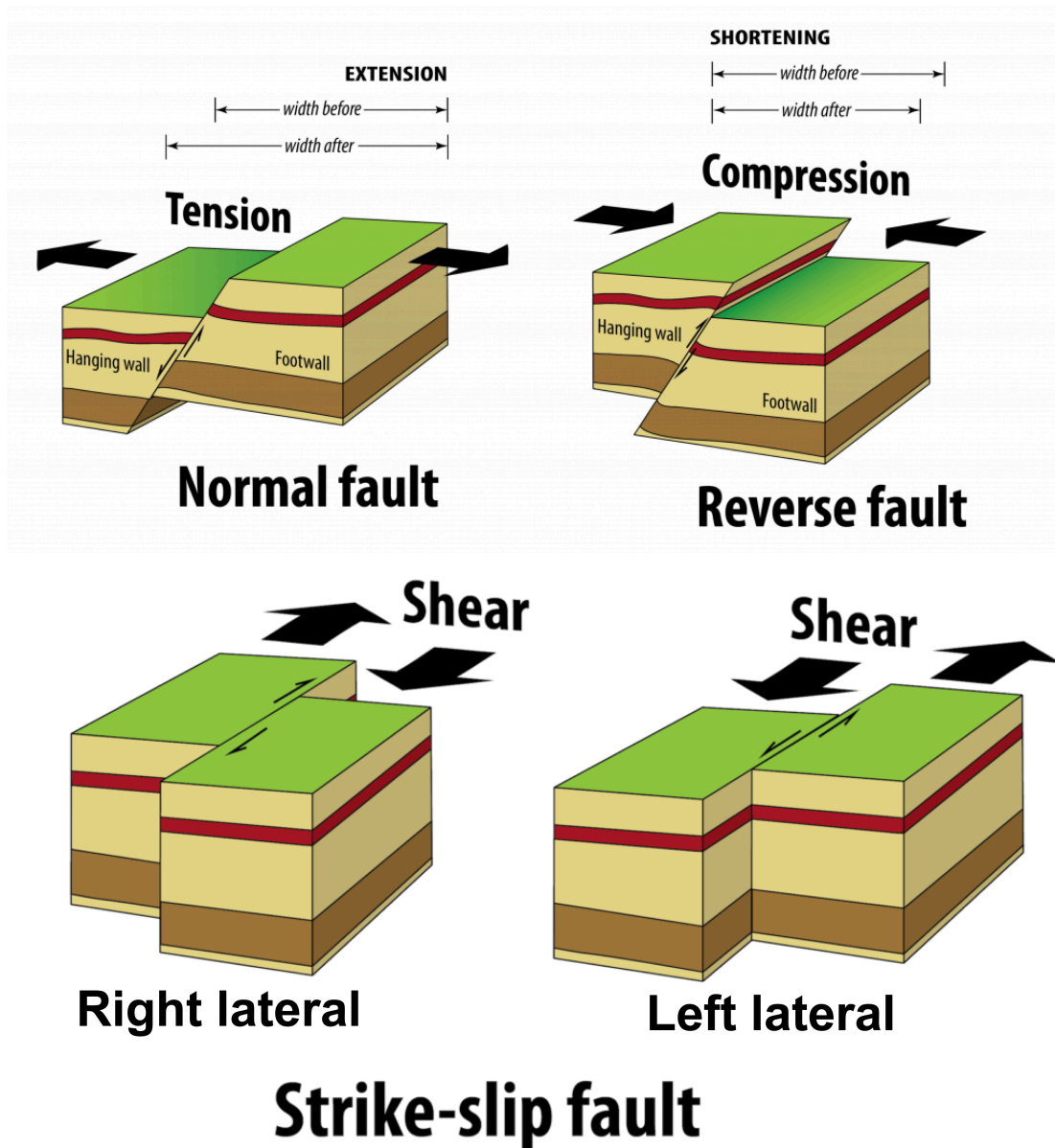


Figure 10.5 – Types of faults. Top: Dip slip faults. Normal faults are caused by tension (divergent tectonics), while reverse faults happen during compression (convergent tectonics). Bottom: Strike-slip faults. Rocks on either side of the fault move parallel to the fault. In right strike-slip faults the far side moves to the right of the observer. In left strike-slip faults the far side moves to the left of the observer. Image Credit: [Karla Panchuk](#), CC BY.

Exercise 10.3 – Identifying Faults

Figure 10.6 shows six photos of faults. Describe the characteristics of these faults by answering the following questions and filling out Table 10.3. Determine which view you are looking at. Remember that images can either be taken from above a feature showing a map view or from the side which is a cross-section view

- On each photo, draw a line for the fault.
- Identify the type of fault shown.
- If a fault is a dip-slip fault, identify the hanging wall and footwall on the photo and the approximate angle of the fault from the ground level.
- If it is a strike-slip fault, identify if it is left-lateral or right-lateral.
- Give the tectonic setting needed to create it.

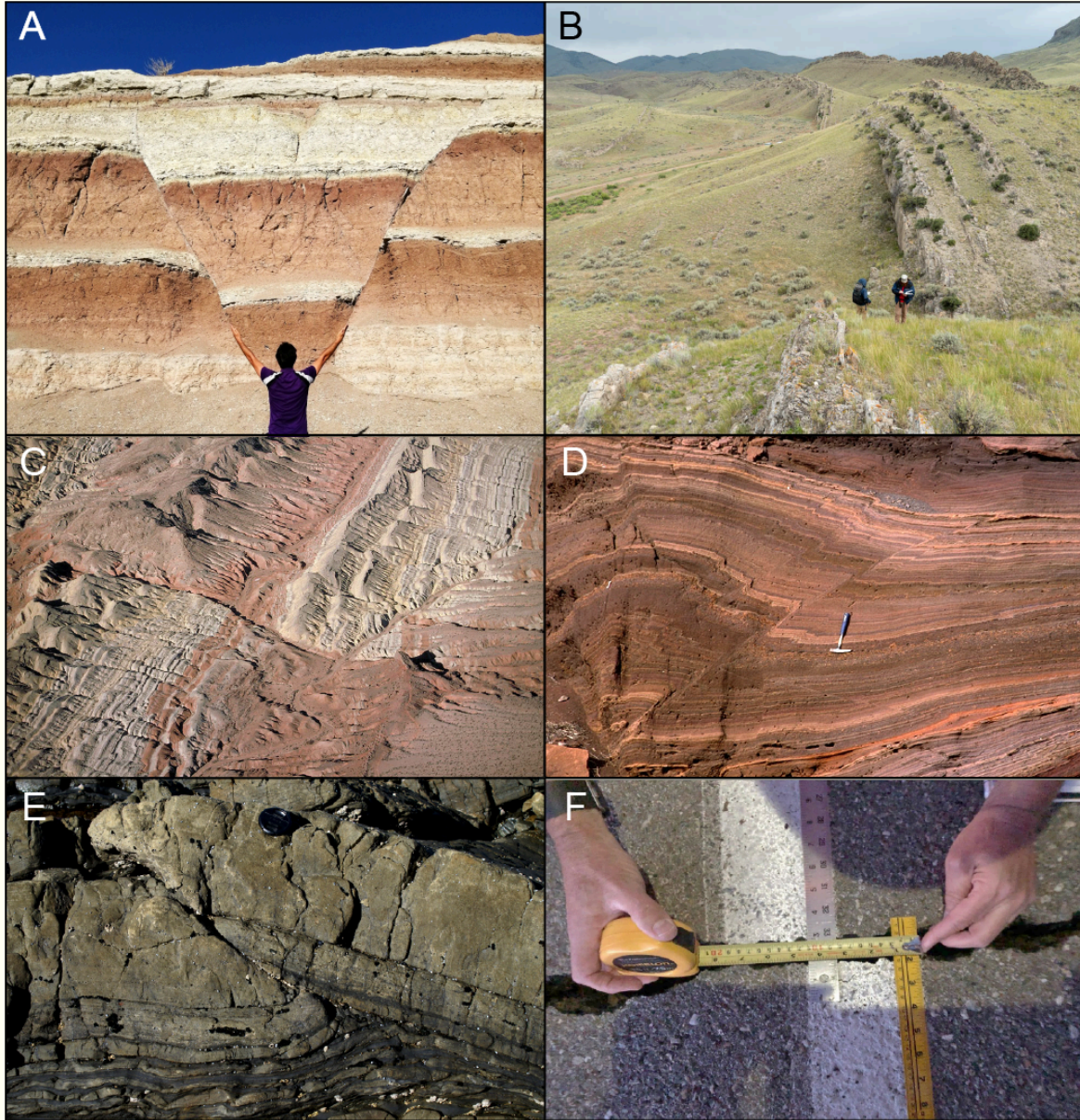


Figure 10.6 – Six images of brittle deformation. Images are from: A. Zanzan-Tabriz highway, Iran; B. Southwestern MT, C. Death Valley CA (note road cross-cutting the image); D. southeastern OR; D. Cape Liptrap, Victoria, Australia; D. Highway 176 near Ridgecrest CA. Image credit: A. Mohammad Goudarzi CC BY; B-D Marli Miller CC BY-NC-SA. E. Roberto Weinberg, used with permission, F. Kelly Blake, US Navy Public Domain.

Table 10.3 – Fault features and identification

Photo #	View	Movement Direction	Fault Angle	Fault Type	Tectonic Setting
A					
B					
C					
D					
E					
F					

10.4 Structures in Three Dimensions

Thinking about geology in three dimensions (3D) is difficult. If you practice, this is an ability that you can improve with time. If you can make 3D images of structures, you can figure out structures beneath you. In fact, some geologists say that the structure you see at the surface is similar to what is underneath. Click [here](#) for a 3D image of a fold. Is it the same from the top as well as the side?

Exercise 10.4 – Working in Three Dimensions

Figure 10.7 contains four block models of different types of deformation.

- Complete the remaining sides of the diagrams for Figure 10.7. Identify the type of deformation and its characteristics.

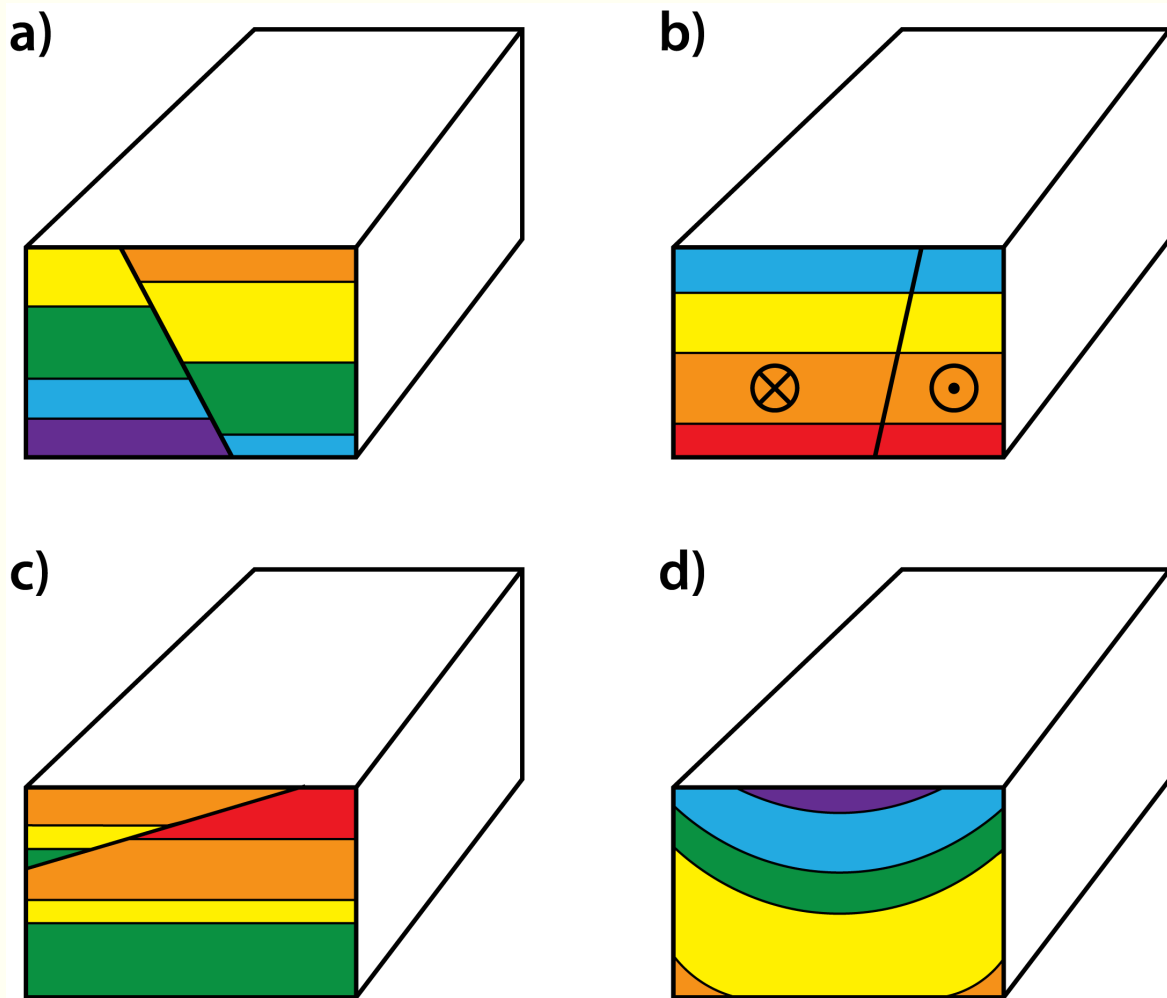


Figure 10.7 – Block models of deformation. In image b, the two circles show the direction of relative movement. The circle with a dot is the side moving towards you whereas the circle with an x is moving away from you. Image credit: Michael Comas CC BY-NC-SA.

b. Which block diagram(s) shows ductile deformation?

- For the blocks with brittle faults, use an arrow to show the relative movement for the hanging wall (side above the fault).
- Indicate on the map view of each block diagram the oldest and youngest sedimentary layers.
- Use what you have learned from completing the block diagrams above to construct a new block diagram of an anticline on Figure 10.8. The block should have four layers colored (from youngest to oldest): red, orange, blue, and purple.

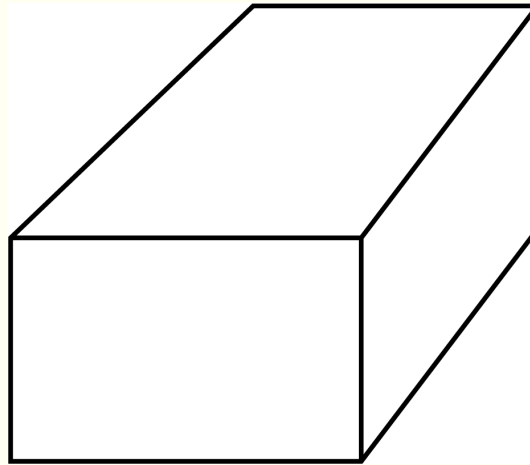


Figure 10.8 – Blank block model.

- f. Are the oldest or youngest sedimentary layers in the center of the fold.

Since it is difficult to do experiments to deform rocks, geologists investigate deformation using analogs and modeling studies. An easy analog to use modeling clay. Start by making a few flat layers of different colors. Then use your hands as if they are two convergent plates and push on two sides of your clay layers. This will make a fold, either an anticline or syncline. Other geoscientists use sandbox models to replicate folds and faults (Figure 10.9). If you like programming in Python, you can try out [GemPy](#) to make your own 3D geologic models. However, for this class, we'll use a simpler web-based program to make your own models of geologic structures.

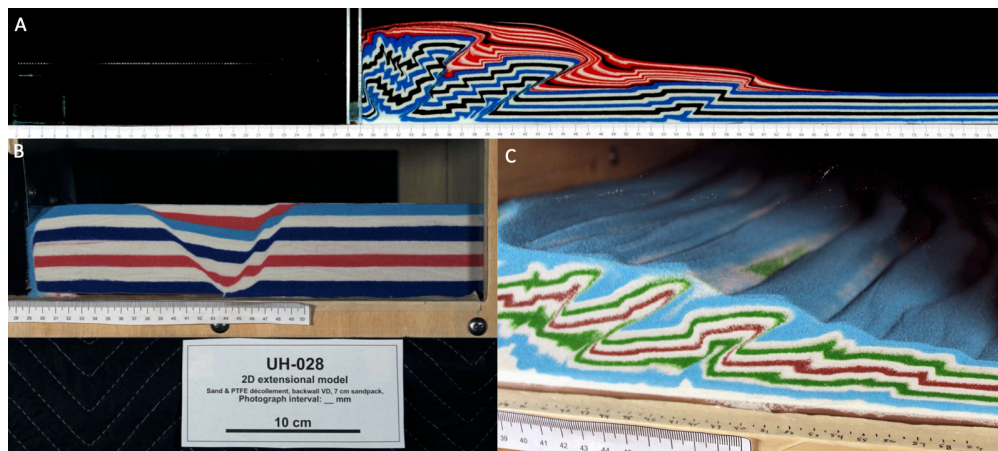


Figure 10.9 – Layers of sand that are deformed to simulate convergence and divergence. These create folds and thrusts (both thrust and normal). A. This sandbox simulates convergent and sedimentation making a thrust belt. This originally was 85 cm long and the back stop has moved 28 cm. B and C are both sandbox experiments done by University of Houston undergraduate students. B – divergent tectonic setting forming a graben with folds and normal faults, C – convergent tectonic setting showing folds developing on the top surface. Note that the right side of the image has only folds and thrust faults develop on the left side. Image credit: Photos from Jonny Wu, CC BY.

Exercise 10.5 – Creating Your Own Geologic Structure

Head to [Visible Geology](#) to create your own geologic structure using the Geology Explorer tab. Click [here](#) if you need help using this website.

- Initially there are 3 layers of the same thickness. Start by adding 3 to 5 more layers. The first layer is the oldest (on the bottom). You can alter the rock name, height and color of the beds using the pen tool.
- Go to the Events tab to add a fold to your model using the Fold menu. You can rotate your model to see it in 3D. Use whatever orientation by changing the strike and dip of the fold axis. Be sure to click apply when finished. In Chapter 11, you will explore some of the other events and faults available in this website.

Answer the following questions.

- What is the color of the oldest bed? _____
- What is the color of the youngest bed? _____
- Is the fold in the center of your block a syncline or anticline? _____
- Are the limbs steeply or shallowly dipping? _____
- Where are the oldest beds in map view (view from the top)? _____
- Describe the differences between the side with the folds to the adjacent view to the right.

Often, geologists make geologic maps to show deformation features (more on that later). Now that satellites can provide images of the entire Earth's surface, the first step in making a geologic map is to interpret satellite imagery. If you are going to work in an area covered by forests, another technique, LiDAR (Light Detection And Ranging) can be used to see below the canopy. For an example of folds shown with LiDAR, click [here](#). Recently, geoscientists have turned to UAVs (unmanned aerial vehicles or drones) to get detailed imagery, creating either digital elevation models or hill shade maps of deformation features.

Geologists have borrowed the “Rule of Vs” to describe the geometry of mapped strata with respect to topography. The Rule also predicts the surface location of strata in areas of poor exposure. In the simplest case where a geologic feature is a vertical plane, the feature is a straight line. In contrast, if the feature is horizontal, the feature follows the contour lines. Keep in mind that the topographical expression of bedding represents erosional remnants of rock layers that once extended above the present surface; a lot of rock has been removed to produce the topography you see today.

Exercise 10.6 – Investigating Geologic Structures Using Google Earth

Use this [Google Earth tour](#) to explore some geologic structures.

- Stop 1 brings you to Canyonlands National Park in Utah. Describe the orientation of the sedimentary rocks.

- b. Are the sedimentary layers all the same thickness? Describe their characteristics.

- c. Has this area experienced any significant tectonic activity? Explain.

- d. Stop 2 brings you to an area near Mexican Hat, Utah. Look at the orientation of the rocks along the yellow line. What is the orientation of the sedimentary rocks on the western, central, and eastern parts of the line?

- e. Create a cross-section along that line. Your cross-section does not have to be to scale.

Table 10.4 – Cross-Section sketch

Cross-Section:

- f. What type of structures is this? _____
- g. Stop 3a brings you to the Spanish Peaks in Colorado. These are ancient batholiths of granitic rock that were exposed at the surface through uplift and erosion of overlying sedimentary rocks. Look at the 3b location. What is this feature? _____
- h. What is the orientation of this feature compared to the West Spanish Peak?

- i. Are there more features like this? Describe their relationship to the peak.

10.5 Structures on a Geologic Map

A geologic map is an important tool for many geologists. These maps show how rocks are distributed in an area, their relationships, and any geologic structures. In addition to the basic map information that you learned about in Chapter 11 (or 2), the age and rock types are described in the legend. As you know from the map you made of a volcano, the color of a unit may indicate its age. In addition, the pattern of the unit can indicate the rock type. There may also be information about faults and folds indicating fold axes and fault types. Other important geologic map data are the **strike and dip** of various features.

As in many other labs, one reason for studying folds and faults is that they are important for understanding and finding economic resources. For this reason, many geologists love anticlines. If an anticline has an impermeable layer such as a shale, it can act as a barrier to fluids moving through the Earth. Consequently, fluids will stop at this layer, trapping water, oil, and gas. Also, fluids can carry strategic elements such as gold. The Hill End anticline in Australia was mined and produced over 60 tons of gold!

For the last 35 years, petroleum geologists have been using 3D imaging to understand geologic processes beneath the surface. Figure 10.10 shows two views of the subsurface below Hungary. On the right side of the figure, there are the sedimentary layers which are relatively flat. These formed in small rift basins. In contrast, in the center of part b, you can see an anticline with several oil wells. So, the anticline formed after **rifting**. This is not evident from the geology at the surface.

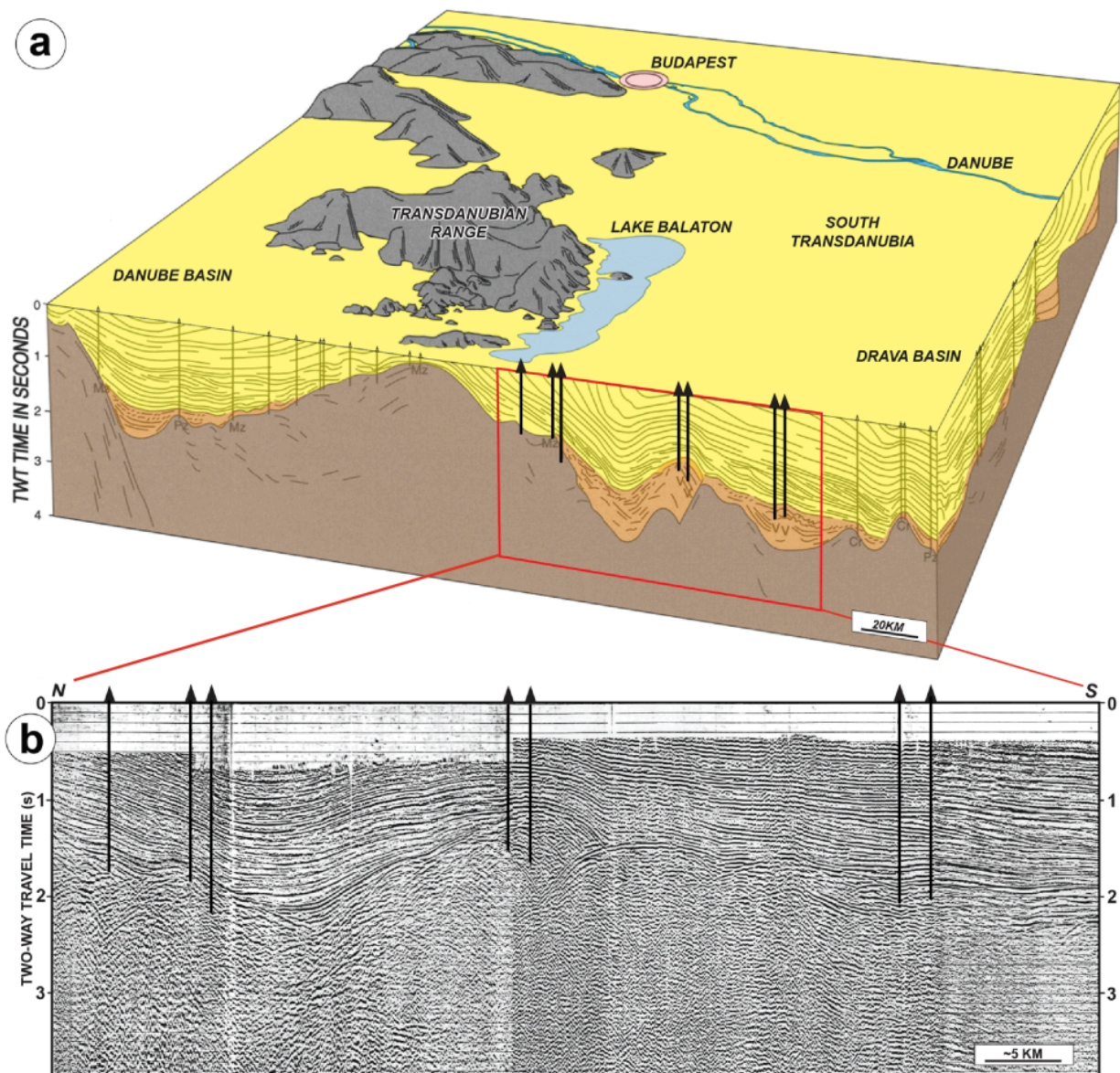


Figure 10.10 Block diagram of the Pannonian Basin, Hungary to illustrate the structure and stratigraphy. The red box shows the location of a seismic cross-section shown in part b. Vertical lines with triangles in both a and b indicate where wells were drilled for oil exploration and production. They are emphasized in part a for wells in part b. TWT = two-way travel time for seismic waves. TWT is used instead of depth for many seismic profiles. In this region, TWT of ~ 2 seconds is about 900 to 1300 m depth. Legend: brown rocks are Mesozoic–Paleozoic bedrock, salmon pink rocks are mid-Miocene strata, yellow rocks are late Miocene to Pliocene strata. Image credit: modified from Tari et al. (2020) CC BY.

Exercise 10.7 – Exploring Geologic Structures Using a Geologic Map

First look at a satellite view of central Pennsylvania (Figure 10.11). Look at the patterns shown by areas with farms and areas with trees. At the top of the image, near the town of Shamokin, there are active coal mines.

A locally famous geologic feature is the “Whaleback” exposed in an abandoned coal mine. If you want to explore this feature as a geology game, click on this [link](#).

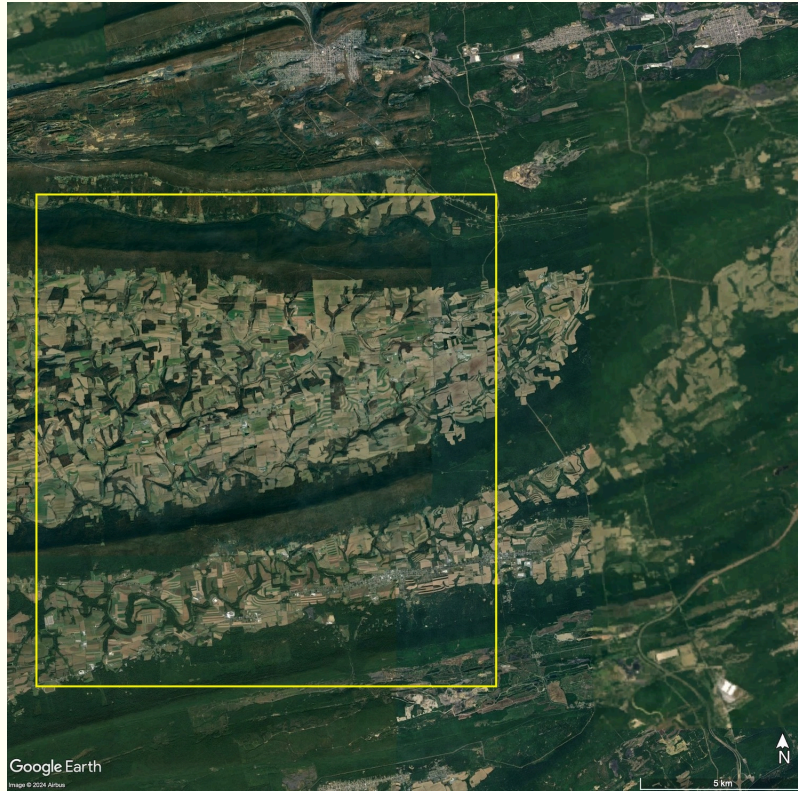


Figure 10.11 – Satellite view of an area in the Valley and Ridge province of Central Pennsylvania. Yellow box shows the outline of the map area in Figure 10.12. Image credit: Google Earth

- a. Using this pattern, what type of deformation would you predict occurred in this area.

- b. Speculate why there are farms in some areas and tree in others.

- c. At the top of the satellite view is the town of Shamokin and at the bottom is the town of Valley View. Why do you think these towns are located in these areas?

Now look at the geologic map shown in Figure 10.12. The important map components are labeled and out-

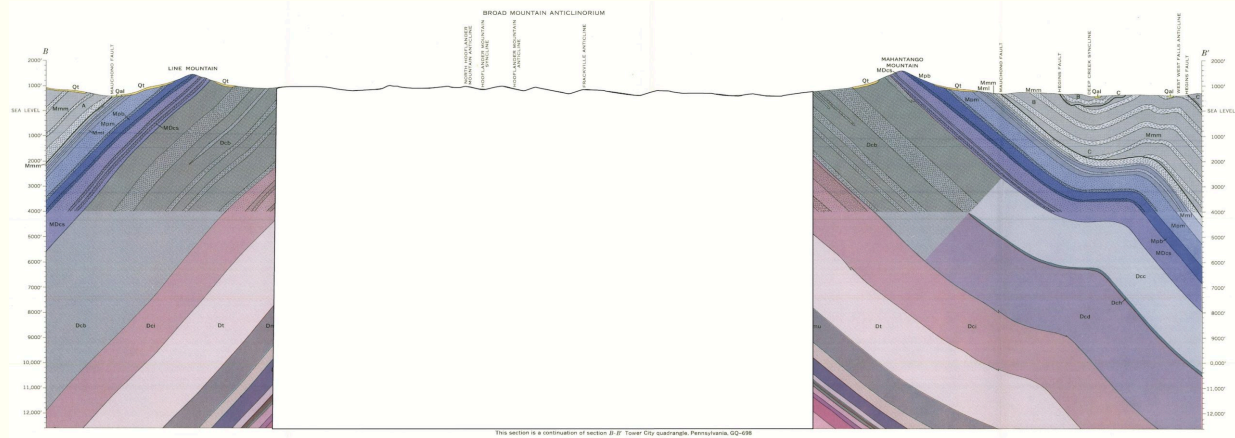


Figure 10.13 – Cross-section of line B-B' highlighted in red from Figure 10.11. Image credit: adapted from the [USGS](#), Public Domain.

- d. Using the legend in Figure 10.12, what are the rock types in this area?

- e. Using the map and the legend, do the rocks become older or younger toward the center of the fold?

- f. Finish the cross-section in Figure 10.13.

- g. Notice that you can see a fold in both cross-section and map view. Why is this?

- h. **Critical thinking:** Pennsylvania has many oil and gas wells as well as coal mines. In fact, the first oil well ever drilled in the US was in Titusville PA to a depth of ~20 m (70 feet) in 1859. Do you think it would be good to drill a well for oil here? If so, how deep would you have to drill? Show your proposed location on Figure 10.12.

Additional Information

Exercise Contributions

Virginia Sisson, Daniel Hauptvogel, and Michael Comas

References

Tari, G., D. Arbouille, Z. Schléder, and T. Tóth, 2020, Inversion tectonics: A brief petroleum industry perspective: *Solid Earth*, v. 11, no. 5, p. 1865–1889, [doi:10.5194/se-11-1865-2020](https://doi.org/10.5194/se-11-1865-2020)

Trexler, J.P. and Wood, G.H., Jr., 1968, Geologic map of the Valley View quadrangle, Schuylkill and Northumberland Counties, Pennsylvania, U.S. Geological Survey, Map GQ-699

CHAPTER 11: GEOLOGIC TIME

Relative Dating and Absolute Dating

Learning Objectives

The goals of this chapter are to:

- Understand the principles of relative dating and apply them to geologic histories
- Evaluate geologic maps for age relationships
- Construct geologic history using radiometric ages

11.1 Principles of Relative Dating

Geologists use two methods for dating events in Earth's history. The first is called **relative dating** meaning how events relate to each other in time, or more plainly, they figure out the sequence of events (what came first, second, third, etc.). Relative dating has no regard for numerical ages. The second method is **absolute dating**, where geologists use radioactive isotopes to figure out the numerical age of a rock or mineral.

Before modern absolute dating methods were discovered and refined, determining the age of rock units was much more difficult. After much debate, the principles of relative dating evolved. While the relative dating methods are less precise, they are still useful in assessing the age of units relative to their contacts or each another. The seven principles of relative dating are:

1. Principle of uniformitarianism – Popularly known as the present is the key to the past. In other words, geologic processes that we observe today have operated in the same manner in the past.
2. Principle of original horizontality – Sediment is originally deposited in horizontal layers due to the force of gravity acting on them. Layers may be deformed tectonically following deposition, but it should always be assumed that the layer started horizontal.
3. Principle of superposition – Within a sequence of sedimentary rock layers, the oldest layer is at the bottom, with the age of each layer decreasing in ascending order so that the youngest layer is on top.
4. Principle of lateral continuity – Sedimentary layers extend laterally in all directions (beyond what may be visible in the outcrop). Therefore, it can be assumed that rock layers on opposite sides of canyons with similar characteristics represent the same layer but have been separated by erosion.
5. Principle of cross-cutting relationships – Features that cut through or modify a rock unit must be younger than the unit they are altering.
6. Principle of inclusions – Any fragments of rock included within another rock must be older than the rock they are contained within.
7. Principle of baked contacts – Magma will metamorphose or “bake” the rocks it comes in contact with. Therefore, if the rocks surrounding an igneous rock have a “baked contact”, they must have been present before the magma cooled.

Together, these are the basis for stratigraphy, a branch of geology concerned with the order and relative position of sedimentary rocks and their relationship to the [geological time scale](#).

Exercise 11.1 – Understanding the Principles of Relative Dating

Explore some of the principles of relative dating below.

Superposition

- Trace out the rock layers on Figure 11.1 and number them, with 1 being the oldest.
- Are the rock layers the same thickness? Which rock layer is the thickest? Which is the thinnest?

- Are the rock layers constant thickness across the image? Can you explain why they are or are not?



Figure 11.1 – Sedimentary rock layers. Image credits: left: Pixabay, Public Domain; right: Wikimedia user Rhododendrites, CC BY-SA.

Original Horizontality

- On Figure 11.2, label the layers that are in their original position and those that are not.
- Are the rock types the lower and upper layers the same? Describe any differences.



Figure 11.2 – Sedimentary rock layers. Image credits: left: [James St. John](#), CC BY; right: [Chris M. Morris](#), CC BY.

Lateral Continuity

- f. Connect the layers across the river on Figure 11.3.
- g. What types of rocks are shown?

- h. Why do some rock units have a vertical face while others have slopes?



Figure 11.3 – The Goosenecks of the San Juan River in southeastern Utah. The current landscape in southern Utah is formed by the tectonic uplift of the Colorado Plateau during the Cenozoic Era. Pre-existing streams on relatively flat landscapes retained their channel courses as they eroded downward through the uplifting plateau. Image credit: [James St. John](#), CC BY.

Inclusions

- i. Which part of the rocks in Figure 11.4 are the inclusions? Circle them.
- j. Are the inclusions older or younger than their host rock?



Figure 11.4 – Left: Peridotite mantle xenolith in a unique basalt from Arizona. Right: Metamorphic xenoliths in an ultramafic dike. Image credits: left, [James St. John](#), CC BY; right, [James St. John](#), CC BY.

Cross-Cutting Relationships

- k. In Figure 11.5, use cross-cutting relationships to determine which rocks are older.
- l. How many generations of igneous rocks are there in each photo?



Figure 11.5 – Left: Andesite dike from Wyoming. Right: Felsic dikes and diorite from California. Image credits: left, [James St. John](#), CC BY; right, [James St. John](#), CC BY.

11.2 Unconformities

The geologic record is not like a video recorder that documents every single event in Earth's history. There are times when nothing significant happens in the geologic time record, or the record is "deleted". If there is erosion during this time, this leaves a time gap or **unconformity**; a contact between two rocks that represents a period of erosion. This means that even though the rocks touch each other, there is a difference in age. Sometimes the erosional surface will develop a soil layer and sometimes it is just rock. So, you can look for soil on the surface to determine if there has been a gap in time.

Simply speaking, an unconformity is a pattern that you look for in a group of rocks that tells you erosion has taken place. Rocks exposed on the Earth's surface are affected by physical and chemical weathering processes that work to break them into smaller pieces or dissolve them in water. This material is then transported away by wind, water, or ice, a process known as erosion. Many people use weathering and erosion interchangeably, but they do mean different things: weathering is the breakdown of rocks, while erosion removes the broken down material.

There are three types of unconformities we'll focus on, and each forms in a slightly different way. They all involve sedimentary rocks, changes in sea level, and/or uplift from an orogeny. Each unconformity tells a unique story of the geologic history of the area they've been found.

1. A disconformity is an erosional surface where the rocks below the unconformity are much older than the rocks above. This type of unconformity typically forms when horizontal layers of sedimentary rock are deposited in a shallow marine environment; then sea level lowers to expose these rocks and allows erosion to occur; then sea level rises again, and new horizontal layers of sedimentary rock are deposited. Erosion removed some of the original rock, creating a large age gap

between the rocks above and below the erosional surface.

2. A nonconformity forms when igneous or metamorphic bedrock is eroded, and then horizontal layers of sedimentary rock are deposited directly on top of it. The unconformity is where the bedrock meets the sedimentary rock. For example, when a mountain belt is eroded below sea level, and afterward sediments are deposited on top of the igneous or metamorphic rock.
3. An angular unconformity is created when horizontal layers of sedimentary rock lie on top of tilted layers of sedimentary rock. For this to occur, sedimentary rocks deposited in the marine environment are lifted above sea level by a tectonic event, which causes the sedimentary rocks to become tilted or folded. Since these rocks are exposed above sea level, erosion takes place. The rocks can either be eroded below sea level, or sea level can rise, which would allow new, horizontal layers of sedimentary rock to be deposited on top of the tilted ones. This creates an angle between the younger, horizontal layers on top and the older, tilted layers below.

Exercise 11.2 – Looking at Unconformities

Unconformities can be confusing and difficult to identify if you are not an experienced geologist. Look at the following 3D models of unconformities. Investigate the labels and explore these outcrop models.



One or more interactive elements has been excluded from this version of the text. You can view them online here: <https://uhlibraries.pressbooks.pub/physicalgeologylab/?p=406>

[Unconformity and faults, USA](#) by [Sara Carena](#) on [Sketchfab](#)



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[Unconformity, Germany](#) by [Sara Carena](#) on [Sketchfab](#)

Now that you have seen some unconformities in outcrop, you can work to identify them on your own. The four models below are unlabeled outcrops with an unconformity. Take your time to study the outcrop, then make a quick sketch of each outcrop in Table 11.1, making sure to identify the unconformity. Do not worry about your sketches looking perfect. Sketches should take about a minute each and should only capture the essential features of the outcrop.

Model 1



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Model 2



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Model 3



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Model 4



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Table 11.1 – Model sketches	
Model 1 Sketch:	Model 2 Sketch:
Model 3 Sketch:	Model 4 Sketch:

Now, you can use all of the principles you’ve learned to interpret the geologic history of a region. You’ll need to look for all events including metamorphism, igneous rocks, deformation (both folding and faulting), unconformities, and sedimentary units. If possible be specific about types of events such as normal faults, mafic dikes, nonconformities, etc. Also, don’t forget about the surface. Most geologic histories end at present day with formation of a landscape that may include erosion, volcanoes, rivers, and lakes. For example, in Figure 11.6, you can see a landscape in the map view that you would not imagine is hiding a complex geological history underneath:

- The sequence of geological events starts with a protolith, which is metamorphosed and folded into a high-grade metamorphic gneiss (rock A) at depth.
- Next, the gneiss is lifted towards the surface and displaced by a brittle fault (G_F). Since the hanging wall is moving upward and the fault is at a shallow angle, this is a thrust.
- Both the gneiss and fault A are crosscut by an igneous granitic intrusion (rock B); its irregular outline suggests it was emplaced as magma into the gneiss. Since igneous rock B cuts both the gneiss and fault, igneous rock B is younger than these.
- Next, the gneiss A, fault G_F , and igneous rock B were exposed at the Earth’s surface and eroded forming a nonconformity indicated with the wavy line (C_U). This created an ancient landscape surface on which sedimentary rock E was deposited.
- Next, igneous basaltic dike D cut through all rocks except sedimentary rock I. Since, the top of dike

D is level with the top of layer C, this establishes that erosion flattened the landscape prior to the deposition of layer I, creating a disconformity (J_U) between rocks D and E.

- Fault H_F cuts across all of the older rocks A, B, E and I, producing a fault scarp, which is the low ridge on the upper-left side of the diagram. This is a normal fault as the hanging wall moved downward.
- The final events affecting this area are erosion of the land surface, rounding off the edge of the fault scarp, and producing the modern landscape with a river cutting across the landscape.

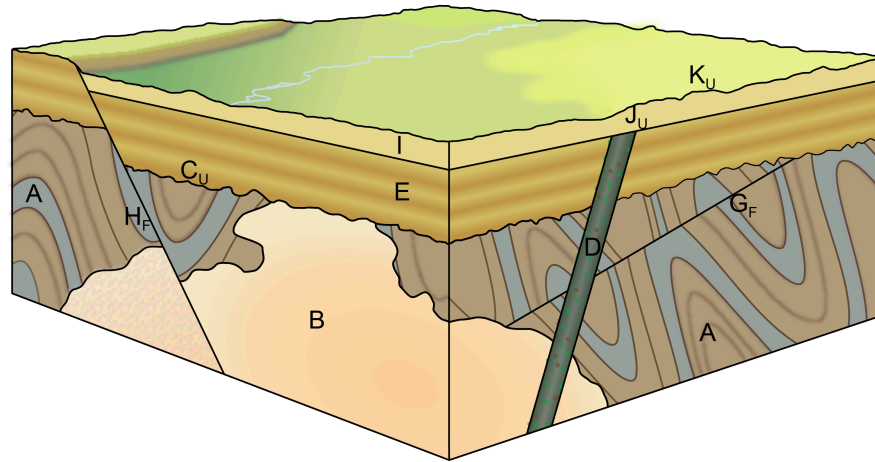


Figure 11.6 Block diagram showing metamorphic gneiss A, igneous (B and D) and sedimentary rocks (E and I) in a stratigraphic sequence. Also shown are two faults (G_F and H_F) and two unconformities (wavy line C_U and straight line J_U).
Image credit: modified from Woudloup, CC BY.

Exercise 11.3 – Sequencing of Geologic Events

Below are several diagrams that represent stratigraphic sections of rock each with a different geologic history. Now be a rock detective and figure out the sequence of events. Each letter represents the deposition of a different layer of sedimentary rock, igneous dike, or geologic event.

- Determine the order of events for the block model in Figure 11.7. Subscripts: F=folding, D=dike, U=unconformity. Hint: it is easier to start with the oldest event or rock unit and work your way forward through time.

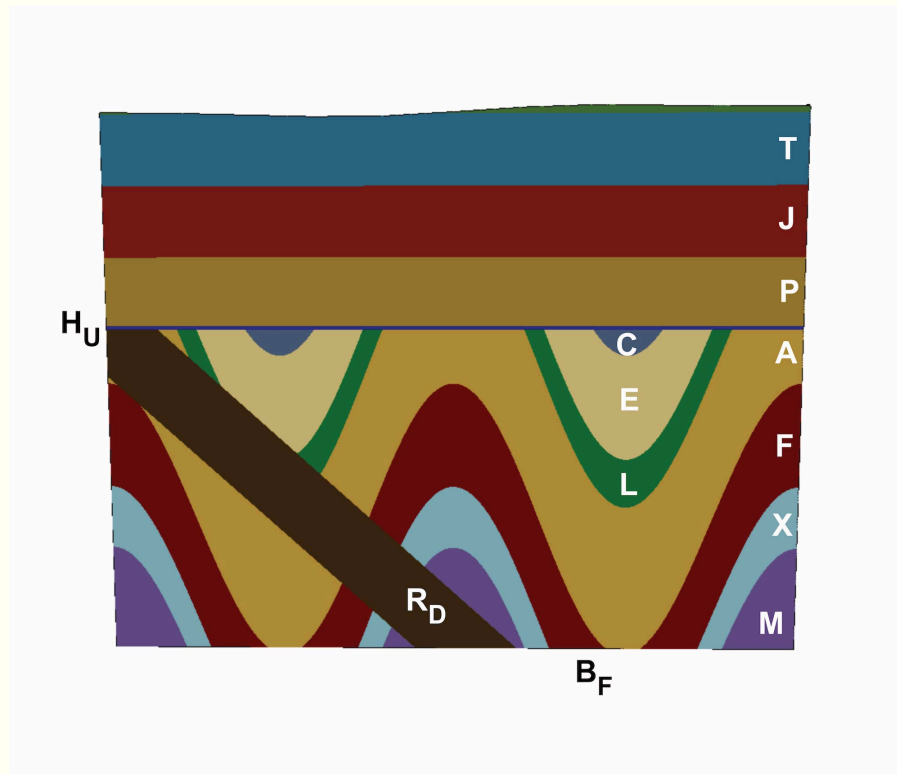


Figure 11.7 – Block model for relative dating created using Visible Geology. Image credit: Virginia Sisson CC BY.

- b. The wooden block model in 11.8 shows several layers of sedimentary rock, a dike, and two faults. Determine the order of events for this block.
- c. Observe the two faults. Give their fault type and sense of motion
- d. Did you learn the Rule of Vs in either Chapter 11 Maps or Chapter 9? In the map view, compare the contacts of the different sedimentary layers shown in yellow to the contacts of the faults and dike. Which are straight versus curved? Why?

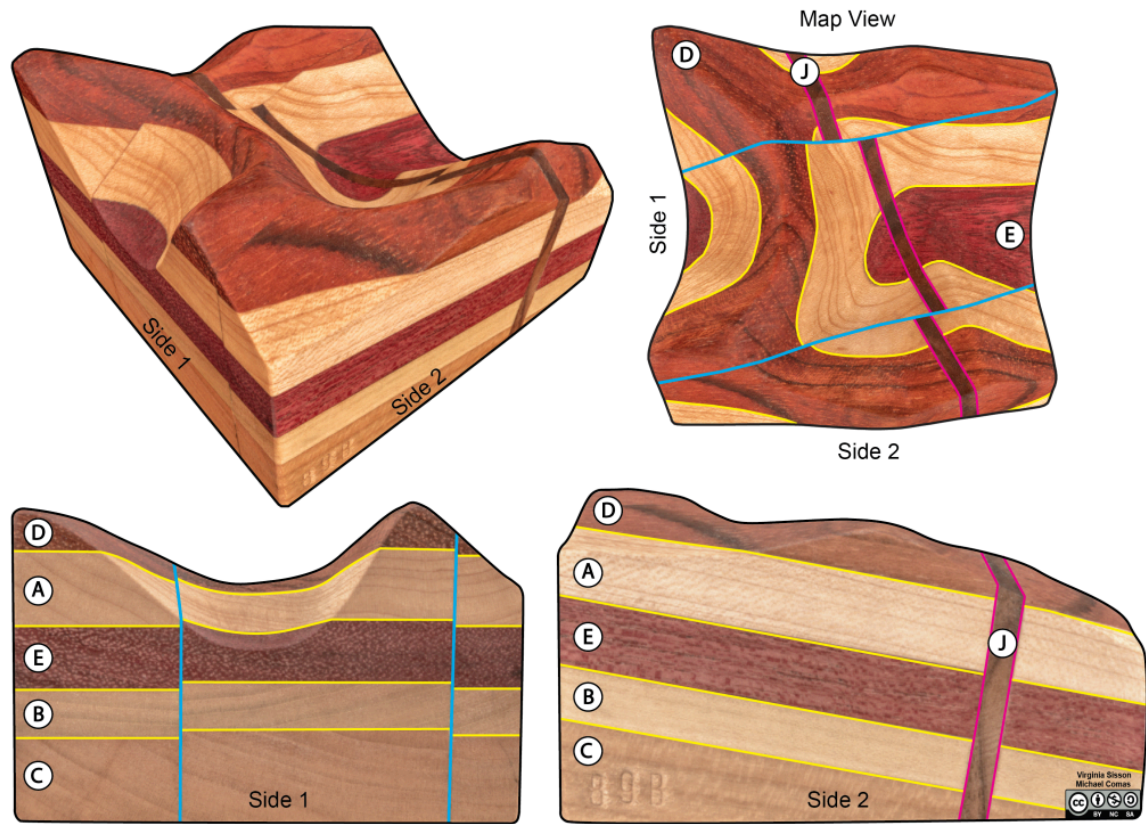


Figure 11.8 – Wooden block model of a fault (block 89b). Letters represent different layers of wood. Yellow lines are contacts between types of wood representing different sedimentary units. Blue lines indicate faults. Magenta lines indicate mafic dikes. One view is down a corner with map view and two sides. Also shown are a map view, side 1 and side 2. Since the wooden block has been carved to look like a land surface, the edges of the map view are not straight. Image credit: Virginia Sisson and Michael Comas using wooden block models created by [Kurtis C. Burmeister](#) with photogrammetry by [Ryan Hollister](#) CC BY-NC-SA.

- e. The wooden block model in 11.9 represents a rift or **graben**. Use Figure 11.9, determine the order of events for this block.

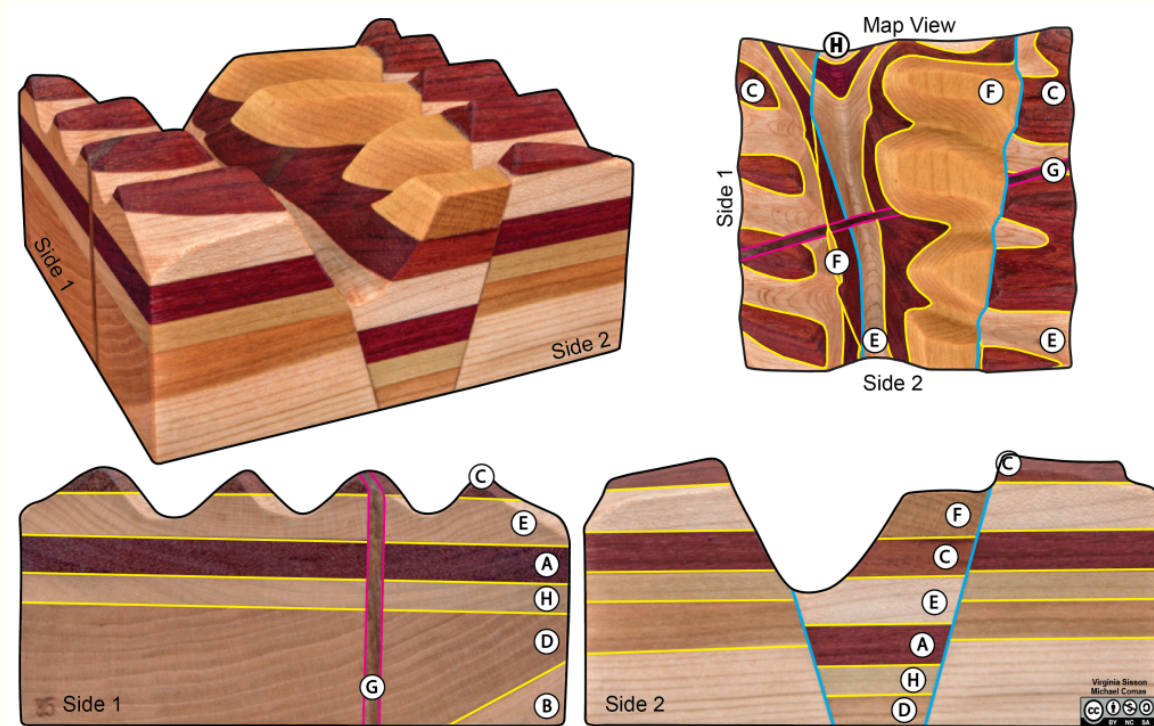


Figure 11.9 – Wooden block model of a graben (block 85). Letters represent different layers of wood. Yellow lines are contacts between types of wood representing different sedimentary units. Blue lines indicate faults. Magenta lines indicate mafic dikes. One view is down a corner with map view and two sides. Also shown are a map view, side 1 and side 2. Since the wooden block has been carved to look like a land surface, the edges of the map view are not straight. Image credit: Virginia Sisson and Michael Comas using wooden block models created by Kurtis C. Burmeister with photogrammetry by Ryan Hollister CC BY-NC-SA.

- f. **Critical Thinking:** Erosion by rivers carves out valleys with the elevation getting lower downstream. Using your geologic history and the map view, which way was a river flowing: toward E or H? Explain.

11.4 Absolute Dating

Geologists can determine numerical ages for the formation of rocks, minerals, and some fossils using radioactive isotope systems. Does radioactivity sound scary? It can be, but what we're talking about is happening on such a small scale that you don't have to worry. The next few paragraphs are a bit technical, but we will try to break it down for you.

An isotope is an atom of an element with a different number of neutrons than protons in its nucleus. For example, a typical carbon atom on the periodic table of elements should have six protons and six neutrons in its nucleus, called carbon-12. Some atoms of carbon can have an extra neutron in the nucleus, called carbon-13, and some can have two extra neutrons in the nucleus, called carbon-14. If an atom has too many neutrons in its nucleus, it can become unstable because the nucleus has too much energy; this is called a radioactive isotope. Carbon-14 is a radioactive isotope.

Radioactive isotopes decay to more stable atoms by way of alpha, beta, and/or gamma decay. In short, radioactive atoms can gain or lose protons, neutrons, and electrons or release energy in other forms

to become stable. For example, carbon-14 radioactively decays to nitrogen-14, a stable product. This [ThoughtCo article](#) gives a very simple explanation of why atoms become radioactive if you want more information.

Radioactive isotopes don't all immediately decay to a stable form because it's a spontaneous process, so it's impossible to predict when and which atom will decay. It's like corn kernels popping in a popcorn maker, you don't know when a kernel will pop, but you know it will happen. Scientists have measured the average rate for radioactive decay and call this half-life. Half-life is the time it takes for half of the unstable atoms (parents) to decay to stable forms (daughters) (Table 11.2). For example, the half-life for carbon-14 is 5,730 years, but the half-life for potassium-40 is 1.25 billion years. In a sample with 1 million atoms of carbon-14, 500,000 of these atoms are expected to decay over 5,730 years.

Table 11.2 – Common isotope systems used for radiometric dating and their half-lives

Parent Isotope	Stable Daughter Product	Half-life
Uranium-238	Lead-206	4.5 billion years
Uranium-235	Lead-207	704 million years
Thorium-232	Lead-208	14.0 billion years
Rubidium-87	Strontium-86	48.8 billion years
Potassium-40	Argon-40	1.25 billion years
Samarium-147	Neodymium-143	106 billion years
Carbon-14	Nitrogen-14	5,730 years

Geologists analyze a material's chemistry and figure out the ratio between parent and daughter atoms. This ratio tells geologists how many half-lives, or what fraction of a half-life, has passed. If you know this ratio and the rate of decay for that isotope system, you can calculate how old geologic material is.

The symbols ka (thousands), Ma (millions), and Ga (billions) refer to points in time like a date. For example, the dinosaur extinction occurred at 66 Ma. Geologists also use other abbreviations for lengths of time, including ky, kya, kyr, and k.y. for thousands of years; my, mya, myr, and m.y. for millions of years; and by, bya, byr, and b.y. for billions of years. All four varieties of abbreviations mean the same thing in this case. Here, you would say the dinosaurs have been extinct for 66 myr. If this sounds confusing, you're not alone because even some geologists use all of the abbreviations interchangeably.

Exercise 11.4 – Absolute Dating

For the exercise, your instructor will provide you with a container of marbles. This is an analog for a mineral that we want to determine the age that it formed. Select two colors to work with. One color will be your parent radioactive isotope and the other will be the stable daughter product.

- Parent (P) Color: _____
- Daughter (D) Color: _____
- Number of P "atoms": _____
- Number of D "atoms": _____

To calculate an age, use the age equation: $t = [\ln((P+D)/P)]/\lambda$

- t = time
- P = number of parent atoms
- D = number of daughter atoms
- λ = is the decay constant (different for every isotope system)

- a. How old is your mineral if λ is 1.21×10^{-4} ? _____
- b. **Critical Thinking:** Recall the exercise on accuracy and precision from the first chapter. Do you think your answer is precise? How many marbles would you need to count to get a better precision?

- c. **Critical Thinking:** Compare your result with those of your class. What is the range of ages? If these geologic samples, how would you interpret this data?

11.5 Using Geologic Dating

Absolute dating tells you different things depending on which rock type you are studying. For minerals in igneous rocks, the radiometric age tells you when the mineral crystallized from magma. In metamorphic rocks, the radiometric age of some minerals can give you the age metamorphism took place, but some isotope systems are not affected by metamorphism and can still tell you the age the minerals originally crystallized in the protolith. So, you can determine when the protolith formed and when it became metamorphosed. Other minerals in both igneous and metamorphic rocks, do not retain their daughter isotopes until the mineral has cooled below a certain temperature. This gives you the age the rock cooled below that temperature.

For minerals in sedimentary rocks, the radiometric age only tells you when that mineral crystallized or metamorphosed in its original rock; it doesn't tell you when the sedimentary rock formed. The only way to determine the age of sedimentary rocks is to combine the principles of relative dating with radiometric dating of igneous or metamorphic events that crosscut the sedimentary rocks, such as a dike. Ages of sedimentary rocks can also be determined from fossils.

Relative and absolute dating methods can be useful for developing the stratigraphic history of an outcrop, but when used together, they are even more powerful. For example, when scientists first discovered the famous *Australopithecus afarensis* hominin fossil skeleton nicknamed "*Lucy*" in Ethiopia, they initially estimated her age using the principles of stratigraphy and the occurrence of pig fossils between 3.5 and 2.9 million years ago. Then in 1992, absolute dating techniques were used on volcanic ash beds that were deposited 1 m below Lucy's skeleton; these resulted in a more precise age of around 3.18 million years old. To further refine this age, we can use local sedimentation rates of 14 to 30 cm per 1000 years. This means her age is closer to 3.15 to 3.12 Ma when she was fossilized. So, combining relative, fossil, and absolute age techniques can be beneficial to better constrain events on Earth.

Exercise 11.5 – Combining Dating Techniques

Figure 11.10 is a hypothetical outcrop view of several sedimentary units that have been deposited on top of a

metamorphic bedrock. There are also three igneous events. The age of metamorphic rocks and igneous events can often be found by using radiometric dating methods, but the age of the sedimentary layers can only be determined through cross-cutting relationships with the igneous and metamorphic rocks.

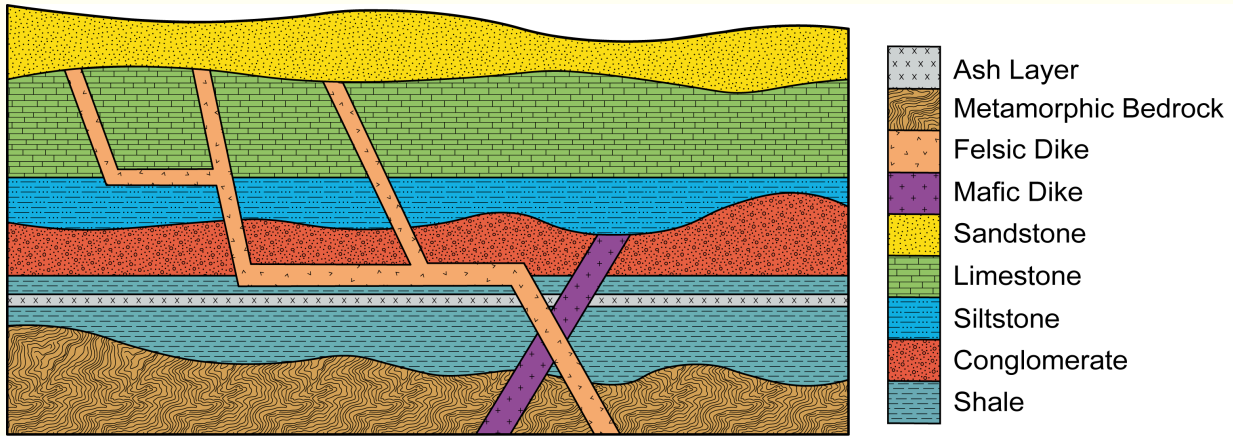


Figure 11.10 – Hypothetical outcrop of igneous, sedimentary, and metamorphic rocks. Rock symbols are standard USGS patterns. Image credit: Michael Comas, CC BY-NC-SA.

- a. Good news! You've already collected samples from the igneous and metamorphic events to determine their ages. Complete the calculations for each. To calculate an age, use the age equation: $t = [\ln(P+D/P)]/\lambda$.

	Isotope System	Decay Constant	Parent : Daughter Ratio	Age (Ma)
Ash Layer	Potassium-40	5.34×10^{-10}	1 : 0.2	
Metamorphic Bedrock	Rubidium-87	1.42×10^{-11}	1 : 0.0055	
Felsic Dike	Uranium-235	9.72×10^{-10}	1 : 0.05	
Mafic Dike	Potassium-40	5.34×10^{-10}	1 : 0.13	

Figure 11.11 – Calculations for the igneous and metamorphic rocks.

- b. Now that you know the age of the igneous and metamorphic events, determine the minimum and maximum ages for the sedimentary layers and what time periods they are from.

	Age Minimum (Ma)	Age Maximum (Ma)	Geologic Period(s)
Sandstone			
Limestone			
Siltstone			
Conglomerate			
Shale			

Figure 11.12 – Determining the age ranges for the sedimentary rocks.

- c. What are the approximate ages of the four unconformities (indicated by the wavy lines)?

- d. Now that you have ages for all the events place them in order from oldest to youngest. Determine the order of events for this outcrop.

- e. Do you think the unconformity above the metamorphic bedrock formed relatively soon after the rock's formation or long after?

While topographic maps are useful for looking at topography, often times geologists are interested in the geology of a region. A geologic map is a type of map that provides information on the geologic features and formations of a particular area. It can be used to understand the distribution, composition, and relationships of rocks, minerals, and other geologic features. Additionally, you can use a geologic map to deduce the area's geologic history.

Geologic maps use various colors, patterns, and symbols to represent different rock types or rock units, geological formations, faults, folds, and other geologic structures. Key elements commonly found on geologic maps include rock units, stratigraphic formations, folds and faults, and topography.

Exercise 11.6 – Age relations on a geologic map

Figure 11.13 highlights the different parts that are common on geologic maps. These include the map, cross-sections, explanation of units, scale, location, etc. This map also has locations for economic mineral deposits including silver-lead mines. In this region, over 15 million ounces of silver were produced from 1875 to 1957. Your instructor may provide you with a printed version of the [USGS map](#). Answer the following questions.

- a. Where is this map located in the U.S.?

- b. What is the oldest unit represented on this map? Use the legend to help.

- c. What type of rock is the oldest unit? Be specific and not just igneous, metamorphic or sedimentary.

d. What is the youngest unit represented on this map?

e. Describe the geology of the youngest geologic formation.

f. What is the dominant rock type in this region?

g. Name the geologic structure at the top-center of the map in the Colorado, Kootenai, and Morrison and Swift formations.

h. What is the general trend of the anticlines and synclines in this area? Using the orientation of these structures, what was the orientation of convergent forces?

i. Locate cross-section B-B'. What are some geologic features in this cross-section?

j. Locate the Sagebrush Park stock. This is a granodiorite and quartz diorite intrusive igneous rock. Did the intrusive body intrude into the country rock before or after folding?

k. **Critical thinking:** On the western side of the map, there is another suite of igneous rocks, the Elkhorn volcanics. Are they younger or older than the Sagebrush Park stock? What additional information could you use to determine their age relations?

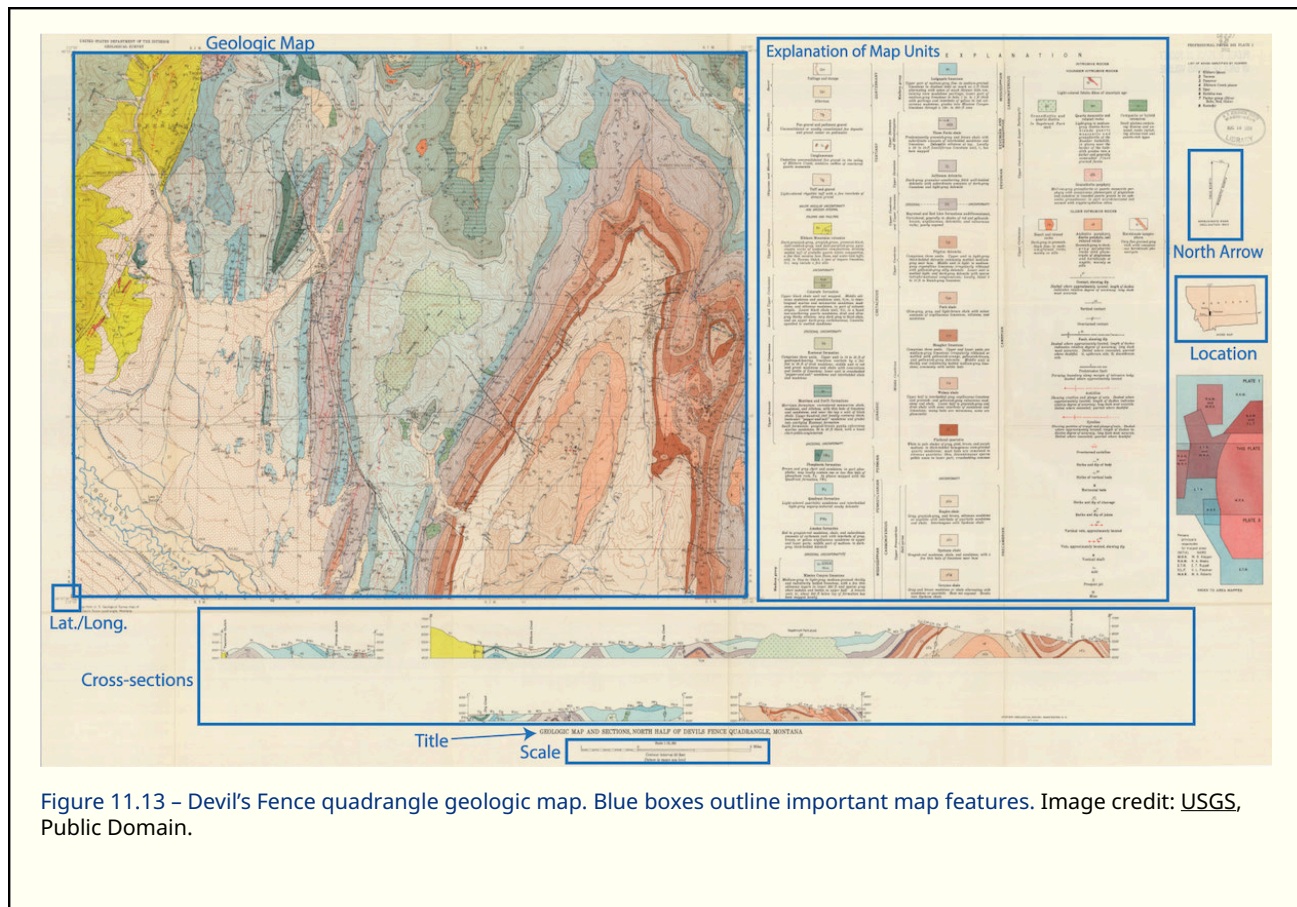


Figure 11.13 – Devil's Fence quadrangle geologic map. Blue boxes outline important map features. Image credit: [USGS](#), Public Domain.

Even though radiometric dating of sediments isn't useful for determining the age of sedimentary rocks, the ages are useful for determining which rocks the sediments were eroded from. This is called provenance. One method for understanding depositional patterns in evolving sedimentary basins is to conduct detrital zircon (DZ) geochronology on different layers. This absolute dating method uses the ages of zircon grains within sandstones to tell how sediment sources changed through time. DZ ages are found by using a mass spectrometer to compare the ratios of radioactive lead and uranium within zircon grains.

As you may have notice in Table 11.2, most radioactive elements have only one parent and daughter. This is not true for uranium (U) as it has two parallel decay schemes with ^{238}U and ^{235}U parent isotopes and a multi-step decay to daughter elements (^{206}Pb and ^{207}Pb). So, instead of using the decay equation, geoscientists use a plot of $^{206}\text{Pb}/^{238}\text{U}$ against $^{207}\text{Pb}/^{235}\text{U}$ for concordant samples of various ages should define a single curve, named 'concordia' by G. W. Wetherill in 1956. For more on U-Pb geochronology, click on this [link](#).

How to measure all these different isotopes for determining mineral and rock ages? Use a mass spectrometer which can measure the mass of a molecule by measuring the mass-to-charge ratio (m/z) of its ion. This technique was first used in 1918 and over the years, two Nobel Prizes have been awarded for advances in mass spectrometry. In the 1950's, geologists first started using this technique for U-Pb analysis. What is the future of this technique? Well, NASA is developing mass spectrometers to go into space (Figure 11.15). So, perhaps we'll be able to remotely do geochronology and determine more about the history of our solar system.

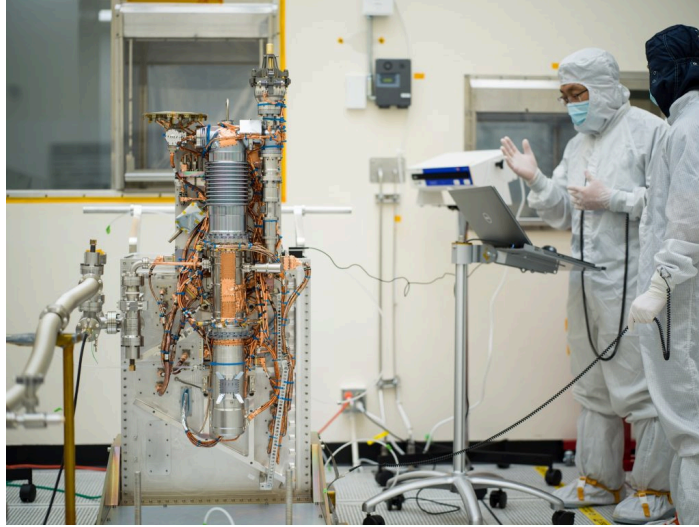


Figure 11.14 NASA engineers prepare a mass spectrometer for a mission to Europa. Image credit: [NASA/JPL-Caltech](#), Public Domain.

Exercise 11.7 – Sediment Provenance

In east-central Texas, the Paleocene Wilcox Group consists of sandstones that house important resources including aquifers, lignite coal and petroleum. To better understand this sediment, you have been tasked with determining its geologic history of an east-central Texas study area (Figure 11.15) using detrital zircon (DZ) geochronology. The U-Pb method of dating is the one usually applied to zircon. This method relies on two separate decay chains, ^{238}U to ^{206}Pb , with a half-life of 4.47 billion years, and ^{235}U to ^{207}Pb , with a half-life of 710 million years.

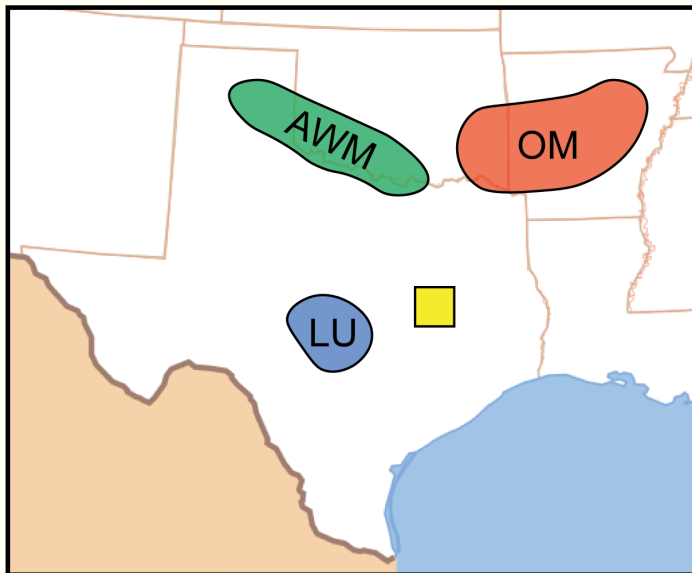


Figure 11.15 – Map showing the study area located in the yellow box. Also shown are three potential source areas for zircon grains. LU = Llano uplift, AWM = Amarillo-Wichita Mountains, and OU = Ouachita Mountains. Image credit: Michael Comas CC-BY-NC-SA; zircon source areas from Wahl et al. (2016).

- a. The first step is to determine the age of the source areas. You've already collected samples from each source and determined their U/Pb ratios (Table 1.3). Use Figure 11.16 to determine the ages of your source areas.

Table 11.3 – U-Pb isotope data for source rocks

Region	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	Age (Ma)
Amarillo-Wichita Mountains	7.5	0.3	
Llano Uplift	4.5	0.25	
Ouachita Mountains	0.5	0.05	

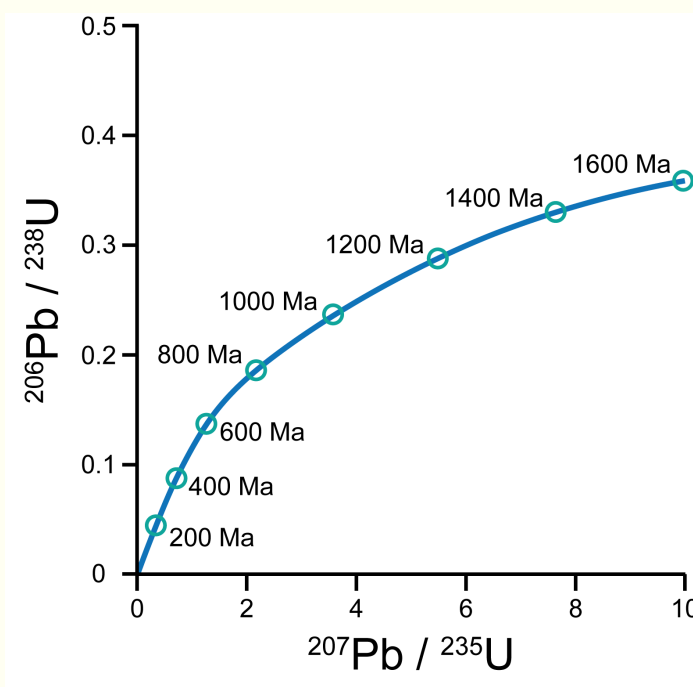


Figure 11.16 – Wetherill concordia diagram for U-Pb. Image credit: Michael Comas, CC BY-NC-SA.

- b. A sandstone from the study area contains many zircon grains with U/Pb ages of ~1100 Ma. Where were these sediments mainly sourced from?

- c. The unit above the sandstone shows U/Pb ages of ~300 Ma. Why do you think these two adjoining units have zircon grains of different ages?

- d. Propose an explanation for what caused the change.

- e. Figure 11.17 is a series of photos from the study area that shows outcrops of the Wilcox Group with fine-grained sandstone. Three sandstone layers have been selected (S1, S2, S3) to determine the provenance of the sediment. Age data from hundreds of zircon grains has been collected and presented in Figure 11.18. Reconstruct the depositional history of these sediments that including where they are sourced from, and an explanation for why sources may have changed through time. The potential source areas remain the same as those you looked at earlier in Table 11.3.

- f. **Critical thinking:** These sample sites are all in drainage basins of paleorivers. These paleorivers collected sediment from the various source areas. Draw the paleorivers on Figure 11.15. How do you think the paleorivers evolved through time?



Figure 11.17 – Photographs of three sample sites for detrital zircon analysis in east-central TX. Site S2 was in a quarry and along the road is only quarried material. S1 is WSW of Thornton TX, S2 is SW of Kosse TX, S3 is SW of Buffalo TX. Image credit from Google Street view compiled by Virginia Sisson; with locations from [Wahl et al. \(2016\)](#).

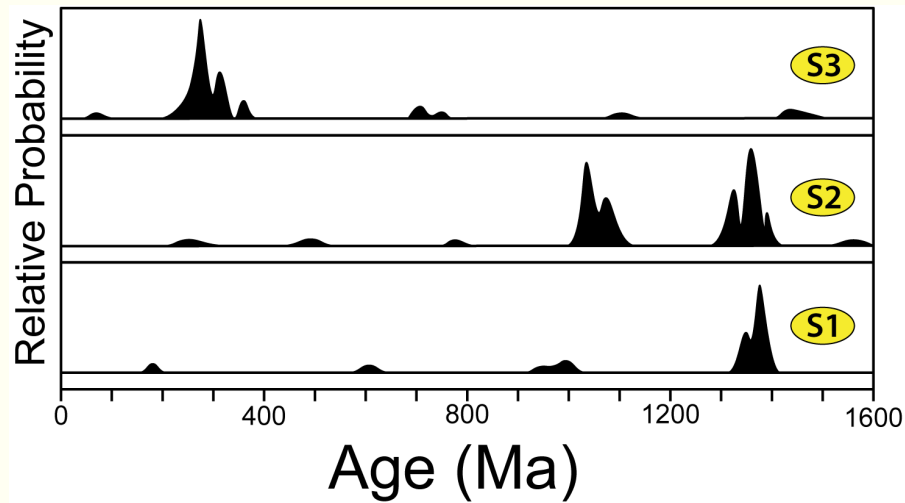


Figure 11.18 – Probability plots of the U-Pb ages from each sample. Image credit: Michael Comas, CC BY-NC-SA; data from Wahl et al. (2016).

Additional Information

Exercise Contributions

Michael Comas, Virginia Sisson, and Daniel Hauptvogel

References

Klepper, MR, Weeks, RA, and Ruppel, ET, 1957, Geology of the southern Elkhorn Mountains, Jefferson and Broadwater Counties, Montana, U.S. Geological Survey Professional Paper 292 [doi:10.3133/pp292](https://doi.org/10.3133/pp292)

Wahl, P.J., Yancey, T.E., Pope, M.C., Miller, B.V., and Ayers, W.S., 2016, U-Pb detrital zircon geochronology of the Upper Paleocene to Lower Eocene Wilcox group, east-central Texas, *Geosphere*, v. 12, p. 1517-1531. [DOI:10.1130/GES01313.1](https://doi.org/10.1130/GES01313.1)

CHAPTER 12: RIVERS

Drainage Basins, Meanders, and Flooding

Learning Objectives

The goals of this chapter are to:

- Understand drainage basins and river patterns
- Interpret meandering rivers using maps and a stream table
- Construct and evaluate hydrographs

12.1 Drainage Basins

Rivers are an important part of the hydrologic cycle as they provide much of the water that is essential for our existence. They provide food, freshwater, and fertile land for growing crops. While water is essential to life, it can be a destructive force too when rivers flood. Rivers are responsible for the creation of much of the topography that we see around us through erosion and transport of sediment.

The area that water flows to form a river is known as a drainage basin, or watershed. All of the precipitation (rain or snow) that falls within a drainage basin eventually flows into its stream, unless some of this water is able to cross into an adjacent drainage basin via groundwater flow. In an idealized scenario, when a single rain drop falls on the Earth's surface gravity will drive it (along with other drops) downslope until it reaches a small stream. This stream will meet a river, and this river will flow into more rivers until it reaches a basin, lake or ocean. This means that where the drop falls will determine where it ultimately ends up. Triple Divide Peak in Montana is the only place in the US, where a drop of snow on the summit may end up in either the Pacific, Arctic or Atlantic Ocean.

Exercise 12.1 – Discovering Drainage Basins

One great tool for visualizing this process across the globe is [River Runner Global](#). This website allows you to drop a single drop of rain anywhere on Earth, and River Runner will determine which path it will take to the ocean.

Your instructor will choose 6 of the 24 points provided on the map in Figure 12.1 to see where that drop would end up. Drop it as close as possible to the number on the map. For each drop, River Runner will provide statistics and show you the path your drop would take. Do not choose all six points from one region.



Figure 12.1 – Twenty-four potential locations to place a drop of water. Image credit: adapted from [River Runner](#).

Refer to Figure 12.1 to complete the following questions.

- a. Before placing any drops, do you think a drop will always end up in the ocean? Why or why not?

- b. In Table 12.1, record the location number, State, number of rivers (and lakes) the drop passes through, the total distance traveled (km), the river that the drop traveled the longest distance in, and the basin it ended up in.

Table 12.1 – River Runner data

No.	State	Number of Rivers	Total Distance (km)	Longest River	Final Basin

- c. Did you notice any rivers that showed up several times in your paths? Which ones? Why do you think that is?

- d. Place a drop on each of the blue points in Colorado. In which basins do the two drops end up? Why do you think this is despite them being so close to one another?

- e. Place a final drop on the red point. Where does it end up? Why?

- f. **Critical Thinking:** Why can some drops travel hundreds of kilometers through only one or two rivers, while others travel tens of kilometers through many rivers?

The movement of water in a stream is driven by gravity, so streams will only flow downhill. We have already learned that moving water is one of the mechanisms for weathering and erosion. Streams weather the materials around them and transport the sediment downstream, leaving behind channels, valleys, and other landscape features. However, many factors can affect how streams shape a landscape, including gradient, flow velocity, amount of water, sediment load, and channel shape and roughness.

The pattern of a stream system is determined by the geology of the underlying material. Is the stream moving over rock or soil? Are there faults, fractures, or other geologic structures?

Exercise 12.2 – Observing Stream Patterns

Instead of following a drop water, observe satellite images of stream networks. Figure 12.2 contains Google Earth Images of four streams with different channel patterns, and Figure 12.3 shows the same streams in black and white. These patterns have specific names, but the goal is for you to recognize and describe these patterns on your own.

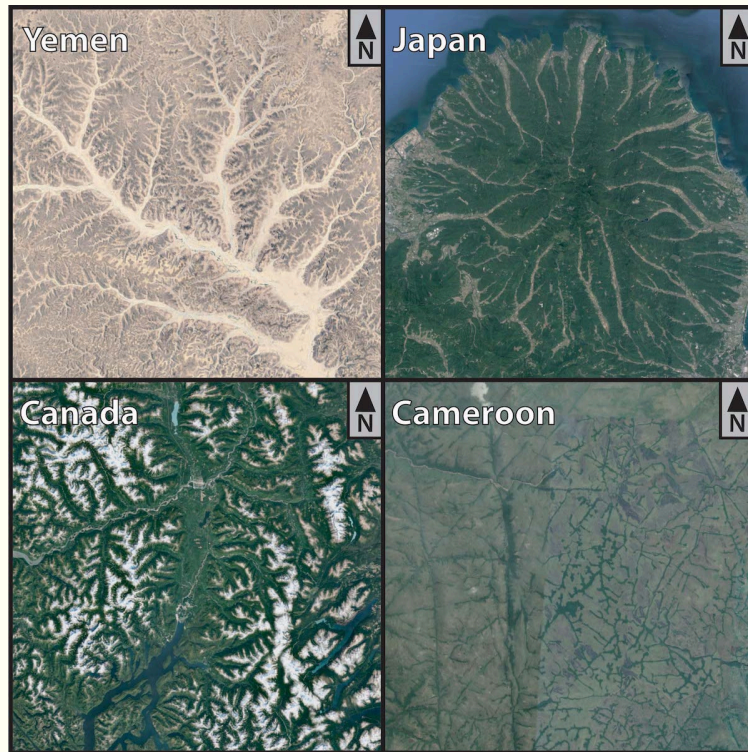


Figure 12.2 – Satellite images of four streams with different patterns. Image credit: adapted from Google Earth.

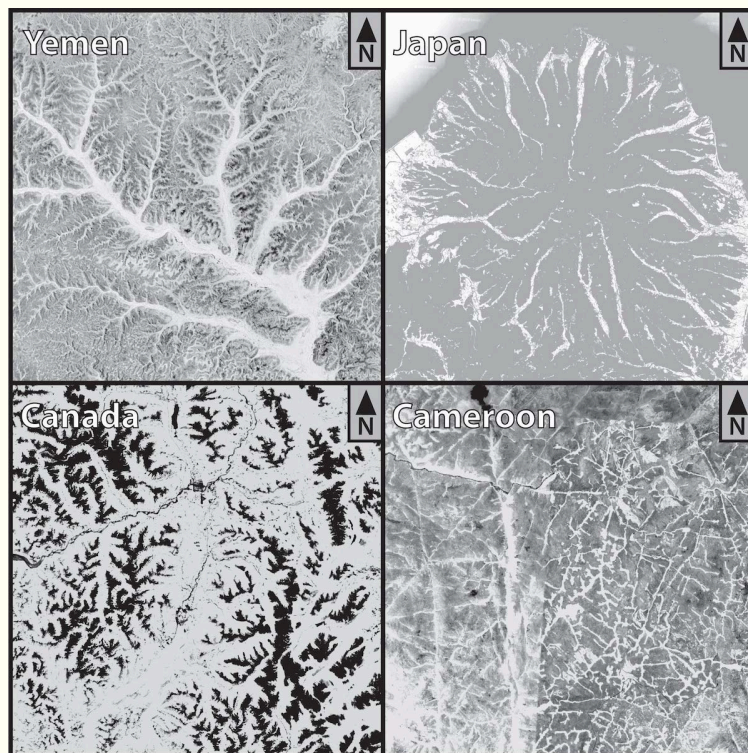


Figure 12.3 – Satellite images of four streams in black and white. Image credit: adapted from Google Earth.

a. Look at the patterns for each stream. Trace the patterns in Figure 12.3 and then describe the drainage patterns.

i. Yemen:

ii. Japan:

iii. Canada:

iv. Cameroon:

b. What do you think is causing the patterns you observed in each stream?

i. Yemen:

ii. Japan:

iii. Canada:

iv. Cameroon:

c. **Critical Thinking:** Do you think some stream types are more common than others? Why?

12.2 Meanders

The flow rate in a stream is related to its gradient, but it is also controlled by the geometry of the stream channel. Water flow velocity is decreased by friction along the stream bed, so it is slowest at the bottom and edges and fastest near the surface and in the middle. In fact, the velocity just below the surface is typically higher than right at the surface because of friction between the water and the air. In a curved section of a stream, called a meander, flow is fastest on the outside and slowest on the inside. Because water flows faster on the outside bend of a meander, erosion takes place. On the inside bend of the a meander, flow velocity is slower and sediment can be deposited. This allows a river channel to migrate horizontally across a landscape.

Exercise 12.3 – Understanding Stream Meanders

Answer the following questions about stream meanders.

- Figure 12.4 is a Google Earth image of the Ontonagon River in Michigan. On the image, mark where sediment erosion is occurring. These are called cut banks.
- Mark where sediment deposition is occurring. These are called point bars.
- What can you conclude about how a river meander can migrate by erosion and deposition of sediment?



Figure 12.4 – Satellite imagery of the Ontonagon River, Michigan. The river flows eastward. Image credit: Google Earth.

- d. Figure 12.5 shows a section of the Brazos River in Texas. Complete the cross-sections for the different time stamps of the river, showing how the meander migrated and what the sediment would look like. In your cross sections, mark the location of the most substantial erosion with a star (*), mark the growth of the point bar with slashes (\\\ or ///, depending on which way the cut bank was moving), and mark where a lake is filling with laminated sediments with stacked lines (==). The first and fifth cross-sections have been completed for you.
- e. What happens to meanders when they get cut off in Figure 12.5?

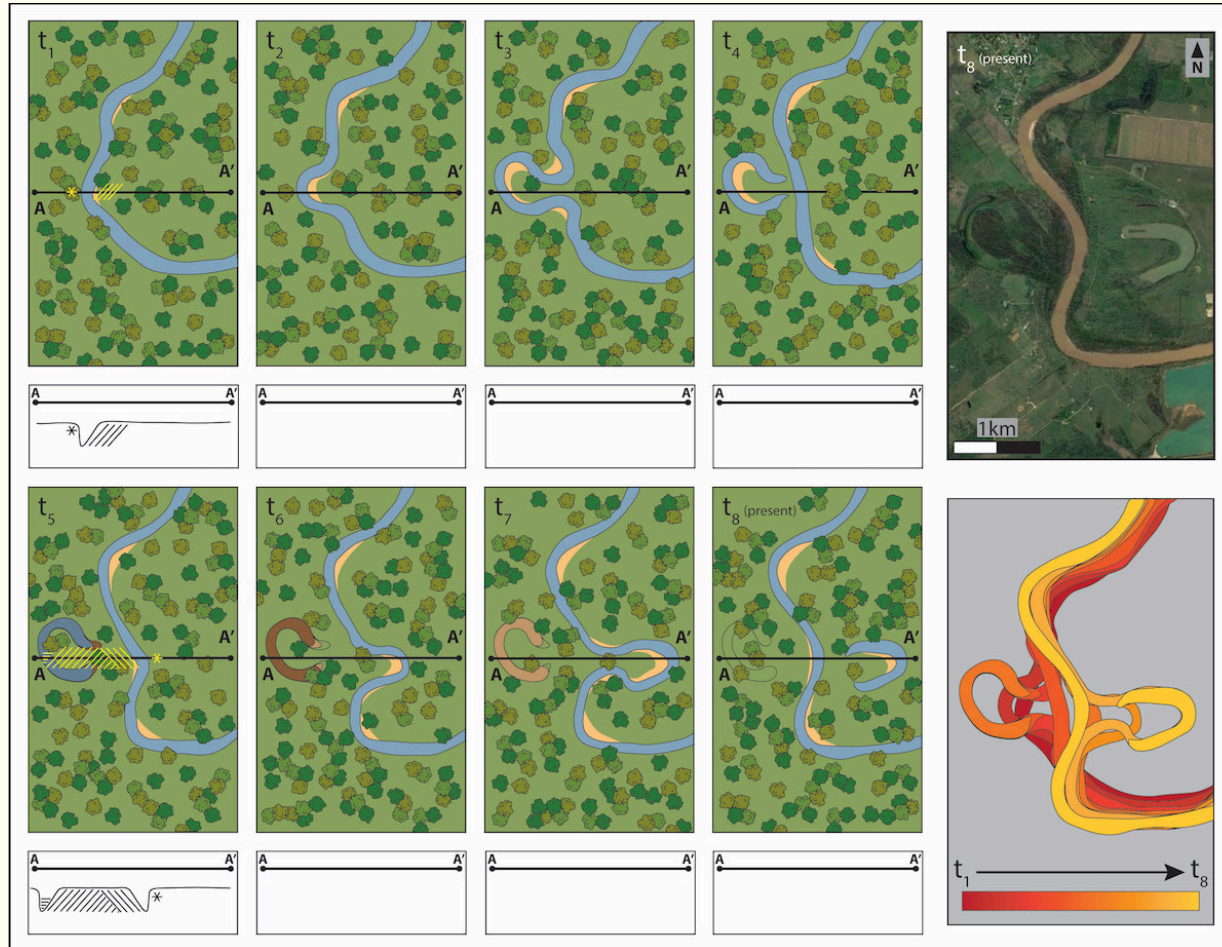


Figure 12.5 – Step-by-step evolution of a meander along the Brazos River in Texas. Image credit: Michael Comas, CC BY-NC-SA

Did you know many borders that separate towns, counties, states, and countries were drawn along rivers? As you've learned, rivers move through erosion and deposition of sediment along meanders. While rivers were used as the marking point to separate localities, the official record of most of these boundaries is denoted by latitude and longitude coordinates. So, while the rivers migrate, these boundaries don't migrate with them. This can cause political issues and border disputes. For example, a land dispute resulted when along the Burundi-Rwanda border in central Africa when a river changed its course due to heavy rains some 60 years ago. Another recent dispute in Kittredge, Colorado was resolved in May 2023.

Exercise 12.4 – State Lines: A Geopolitical Issue

Figure 12.6 is a Google Earth image of the Mississippi River. The river is over 3,700 km long and defines borders or partial borders for ten states. The section in the image is part of the border between Arkansas and Mississippi.

- Determine the path the Mississippi River took when the state borders were originally drawn in 1836.

Some “homes” have been marked on the map for you: blue are in Mississippi and yellow are in Arkansas. Hint: all the blue homes need to be to the right of your line, and all the yellow homes need to be to the left.

- b. It has been almost 200 years since this boundary was drawn. What does that tell you about the timing of river processes compared to most things in geology?

- c. Do you think land (and homes) should remain in the possession of a state even if they are isolated by a river in this way? What do you think the landowners would say?

- d. Explore Google Earth or Google Maps. Can you identify some other borders between localities that would be in a similar situation?

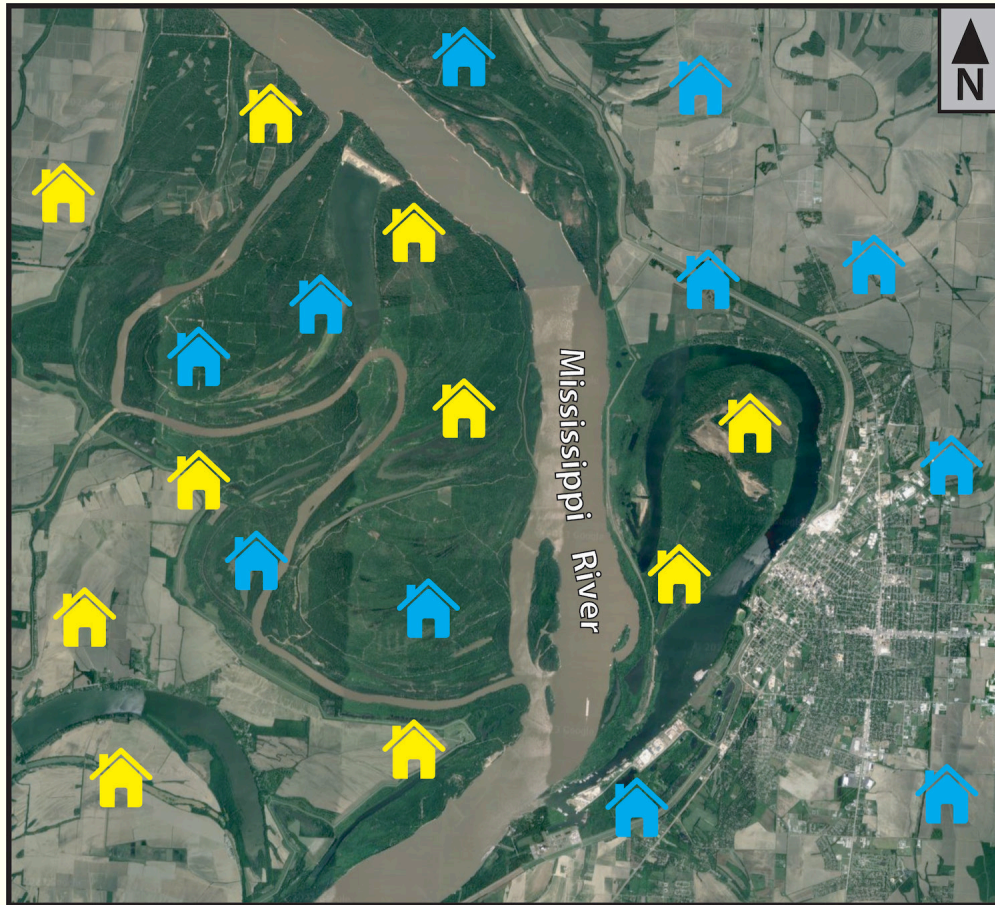


Figure 12.6 – Google Earth image of the border between Arkansas and Mississippi along the Mississippi River. Blue houses are in Mississippi, and yellow are in Arkansas. Image credit: adapted from Google Earth.

12.3 River Modeling

Since it is impossible to experiment with natural rivers, geologists use stream tables with flowing water and moveable media to simulate sediment. River models help us build intuition for processes that otherwise might be hard to visualize. They have the ability to test how a stream erodes, transports, and deposits sediments, which depends on its energy. The higher the energy, the more sediment it can move. Different factors can control the energy level of a stream, including the gradient or slope of the channel. In this lab, we will use modeling to examine the relationship between gradient and different stream types and compare how they erode sediment.

Exercise 12.5 – Modeling Table

Your instructor will take you to the stream modeling table. We have an **EM2 from Little River**.

The stream channel gradient can be controlled using the standpipe. Pull the standpipe up to lower the gradi-

ent and lower the standpipe to increase the gradient. You'll need to change and measure the height of the standpipe throughout this exercise.

Set up the first scenario and let the water run for a few minutes. Answer a-c. repeat for each scenario.

Scenario A

Lower the standpipe all the way into the table outlet to simulate a steep channel gradient and adjust the stream flow to 75 ml/s.

Scenario B

Raise the standpipe so that the top edge is about 3.5 cm above the outlet. This simulates a moderate channel gradient. Leave the flow rate at 75 ml/s

Scenario C

Raise the standpipe so the top edge is about 7.2 cm above the outlet. This simulates a shallow gradient. Leave the flow rate at 75 ml/s.

- a. Measure the following characteristics of the streams on Table 12.2

Table 12.2 – Measured stream characteristics

	Scenario A	Scenario B	Scenario C
Gradient (%)	4	2	0
Channel Length (cm)			
Straight-Line Length (cm)			
Sinuosity (channel length/ straight length)			
Valley Shape			
Valley Width (cm)			
Channel width (cm)			
Valley width/channel width			

- b. What does the part of the stream channel look like?

- a. Scenario A

- b. Scenario B

c. Scenario C

c. What does the sediment load look like (low, moderate, or high)?

a. Scenario A

b. Scenario B

c. Scenario C

d. Where is sediment being eroded and deposited?

a. Scenario A

b. Scenario B

c. Scenario C

e. What is the relationship between gradient and stream channel sinuosity?

f. What is the relationship between gradient and stream valley shape?

g. What is the relationship between sinuosity and the stream valley width to channel width ratio?

h. Based on what we know about the relationship between stream channel energy and erosion, what do you think would happen to stream shape and sediment load if we were to increase the stream flow in exercise in Scenario C from 75 ml/s to 150 ml/s? Why?

12.4 Flooding

Flooding is a common natural disaster, and its results are often fatal. The 1931 Yangtze-Huai River floods in China killed over 1,000,000 people. In addition, the aftermath was devastating with deadly waterborne diseases like dysentery and cholera and those who survived faced the threat of starvation since all the crops were destroyed.

To help monitor rivers for flooding, the U.S. Geological Survey maintains a network of stream gages to monitor discharge, while the National Weather Service maintains meteorological stations throughout the U.S. If you live near a stream, there is a good chance that the water level is monitored as there are over 13,500 stream gauges in the US.

One of the results of a stream gauge is a hydrograph, or a line graph, that depicts water discharge over time for a cross-section within a stream and can show how stream discharge changes following a storm event. Discharge is the volume of water moving through a stream per unit time. In the U.S., discharge is commonly given as cubic feet per second (cfs). A storm hydrograph typically has time on the X-axis and discharge on the Y-axis (Figure 12.7). Sometimes a secondary Y-axis for precipitation is shown. Time typically extends from several hours before a storm event to several hours beyond when the river returns to baseflow conditions. Discharge and precipitation are usually determined remotely using automatic gaging stations.

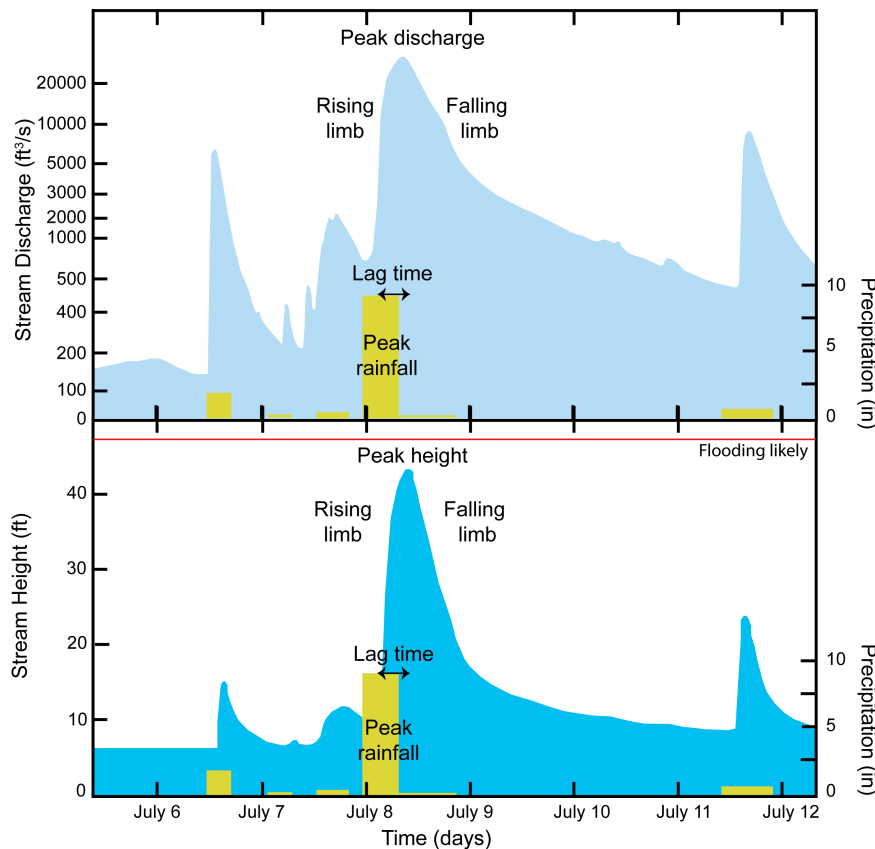


Figure 12.7 – An example of a hydrograph that shows discharge (upper) and stream height (lower). Precipitation is also shown in yellow. This data is from Brays Bayou in Houston, TX for Hurricane Beryl, July 2024. The stream is [monitored by the USGS](#). Image credit: Virginia Sisson, CC BY-NC-SA.

Exercise 12.6 – Create a Hydrograph

Now, let's investigate some stream gauge data for two different streams.

- Table 12.3 contains precipitation and discharge data for two streams. Plot this data on a single graph. The Y-axes should range from 0 to slightly greater than the maximum values (e.g., if the maximum discharge is 1,382 cfs, the Y-axis range should be 0 – 1,400 cfs). Plot discharge on the Y-axis on the left side of the graph; plot precipitation on the Y-axis on the right side. Use bars for precipitation. You should use different colors for each data set.
- What is the lag time for Station A? _____
- What is the lag time for Station B? _____
- What is the peak discharge for Station A? _____
- What is the peak discharge for Station B? _____
- How do the receding limbs on the hydrograph for the two stations compare?

- g. One of these stations is in metropolitan Houston, while the other is in a rural area outside the city limits. Assuming watershed size is equal, which station is more likely to be the one in Houston (A or B)? How can you tell? Hint: consider how lag times might differ in a city versus a countryside.

Table 12.3 – Precipitation and discharge data

Time	Precip. (in)	Station A Discharge (cfs)	Station B Discharge (cfs)
Noon		1298	765
3:00 PM		1291	768
6:00 PM		1287	756
9:00 PM		1293	791
Midnight		1297	772
3:00 AM		1299	758
6:00 AM		1295	764
9:00 AM		1297	782
Noon	0.5	1376	2845
3:00 PM	0.6	1456	3988
6:00 PM	1.1	2245	5882
9:00 PM	0.8	2578	6667
Midnight	0.6	2897	5058
3:00 AM		3218	3982
6:00 AM		3456	2791
9:00 AM		3877	2362
Noon		4168	2023
3:00 PM		3935	1676
6:00 PM		3812	1348
9:00 PM		3634	1201
Midnight		3502	1032
3:00 AM		3371	967
6:00 AM		3013	903
9:00 AM		2878	854
Noon		2615	827
3:00 PM		2467	792
6:00 PM		2271	788
9:00 PM		2119	781
Midnight		2032	783
3:00 AM		1964	789
6:00 AM		1849	782
9:00 AM		1792	778
Noon		1706	780

Additional Information

Exercise Contributions

Michael Comas, Lisabeth Arellano, Virginia Sisson, and Daniel Hauptvogel

References

Klepper, MR, Weeks, RA, and Ruppel, ET, 1957, Geology of the southern Elkhorn Mountains, Jefferson and Broadwater Counties, Montana, U.S. Geological Survey Professional Paper 292 [doi:10.3133/pp292](https://doi.org/10.3133/pp292)

CHAPTER 13: LANDSCAPES

Dunes, Glaciers, Karst, and Subsidence

Learning Objectives

The goals of this chapter are to:

- Understand forces that change the landscape in different environments
- Interpret rates of change of landscapes
- Evaluate the impact of landscape changes on humans

13.1 What is Geomorphology?

Geomorphology (from Ancient Greek: *geo* “earth”; *morphe*, “form”; and *logos*, “study”) is the scientific study of the origin and evolution of topographic and bathymetric features generated by physical, chemical, or biological processes operating at or near Earth’s surface. Geomorphologists seek to understand why landscapes look the way they do, to understand landform and terrain history and dynamics, and to predict changes through field observations, physical experiments, and numerical modeling.

Many forcing agents control the shapes of landscapes, with streams being the dominant force in most continental regions. Other forces include gravity, wind, glaciers, oceans, wildfires, people, and even water beneath the surface. Also important is climate – more about that in Chapter 15.

13.2 Desert Landscapes

The first landscape to explore is deserts, which are mainly affected by wind, and large sand dunes are a common feature. Desert sand dunes commonly form when there is an abundant sediment supply, and wind is strong enough to transport the sand. Dunes form where a dry climate prevents vegetation from interfering with their development. Sand dunes, however, are not restricted to deserts and can be found along seashores, along streams in semiarid climates, in areas of glacial outwash, and where sandstone bedrock disintegrates to produce an ample supply of loose sand.

Two main factors dictate dune shapes: the amount of loose sediment and whether there is one or more prevailing wind directions. The strength, direction, and persistence of winds help determine how dunes develop. In some areas, winds will blow in one direction during the summer and another in winter. In other areas, there may be multiple wind directions. This variability in wind changes the shape of the dunes as well as their names (Figure 13.1). Sand is pushed or bounces (saltation) up the shallow side and then slides down the steep side (slip face). This characteristic shape is easy to see from a side view but harder to see in map view.

Vegetation acts as a barrier to wind, so sand may build up behind the vegetation. Vegetation also makes the sand surface rougher, which can affect sand movement. Also, deep roots can stabilize sand and prevent it from moving. These effects significantly impact sand dunes along the coast and at the edge of a desert where there is enough moisture for plants to grow.

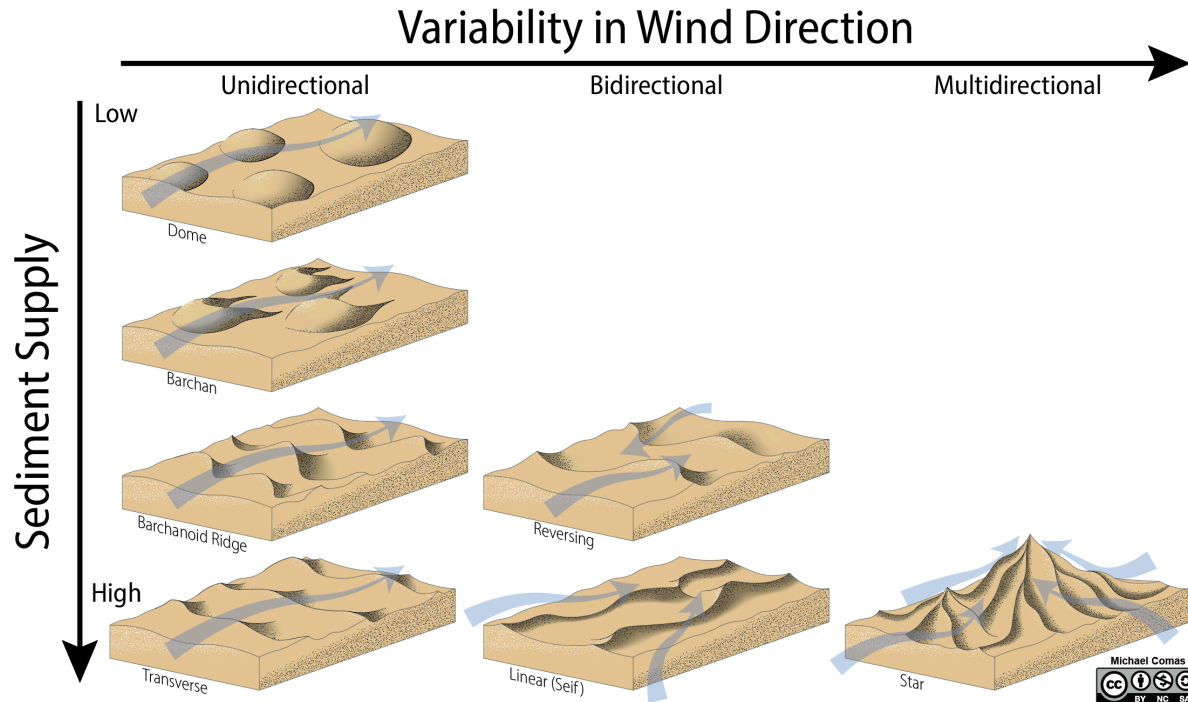


Figure 13.1 – Interplay of wind direction and sediment supply on the shapes of dunes. Image credit: Michael Comas CC BY-NC-SA adapted from [Edwin McKee/USGS](#), Public Domain.

Exercise 13.1 – Observing Sand Dunes

Figure 13.2 shows different types of sand dunes. Answer the following questions about them, and be sure to look at the scales on each image to get a sense of their size.

- Observe the similarities and differences between the dunes in each photo. Trace the crest of as many dunes as possible.
- For each image, describe the geometry of the dunes.

i. Tenere Desert, Niger:

ii. Gran Desierto, Mexico:

iii. White Sands National Park, NM:

iv. Caraveli, Peru:

v. Huachachina, Peru:

vi. Wadi Al Hajaa, Libya:

- c. On each image, draw arrows to indicate the wind direction(s). Some may have more than one prevailing wind direction.
- d. List the dunes in order of increasing sediment supply. Explain.

e. What do you think gives the sands of White Sand Dunes National Park their color?

f. Do you notice vegetation in any of these arid settings?

g. How do you think vegetation affects dune formation?

h. **Critical Thinking:** Why can dunes vary in shape at different scales?

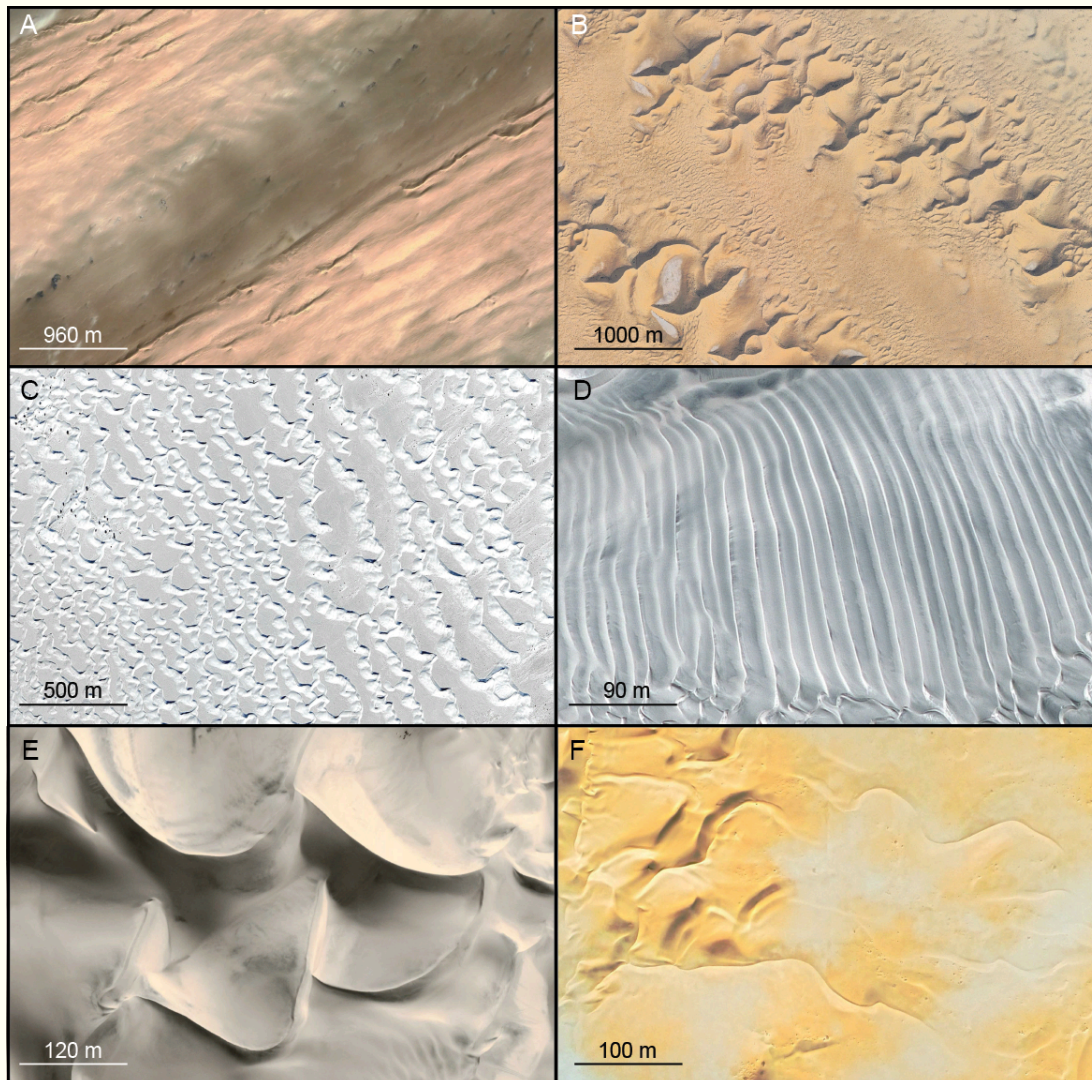


Figure 13.2 Dunes from six different locations. North is to the top in each image. A. Tenere Desert, Niger (16.272, 19.923) image taken 3/2024; B. Gran Desierto, Mexico (31.994, -114.405) image taken 10/2022; C. White Sands National Park, NM (32.918, -106.318) image taken 12/2023; D. Caraveli, Peru (-15.158, -74.718) image taken 6/2009; E. Huachachina, Peru (-14.102, -75.805) image taken 8/2022; F. Wadi Al Hajaa, Libya (27.292, 12.303) image taken 1/2024. Image credit: adapted from Google Earth.

Exercise 13.2 – Measuring Dune Migration

This movement of sand is emerging as a significant problem as **desertification**, or the process by which land becomes desert, is threatening about one fifth of the world's lands. In fact, the [United Nations](#) has declared this to be our planet's greatest environmental hazard and predicts over 50 million people will be displaced by this process in the next ten years.

One of the filming locations for the Star Wars movie series was in the [Saharan desert of Tunisia](#), where sand

dunes migrate across the landscape. Since the set was built in 1976, it has become a tourist attraction. Figure 13.4 shows four Google Earth images of the set from different times over a 5.5-year period. A single barchan dune is outlined with a red dashed line. A barchan dune is crescent-shaped and has a shallow side and a steep side. Wind transports sand up the shallow side of the dune, and sand tumbles down the steep side. Based on the images, you can see that the barchan dune is approaching the film set, which is a problem for this popular tourist attraction. Let's figure out the rate at which this dune is moving.

- a. Three points of the dune have been marked with a yellow dot: the northern point, central, and southern point. Measure the distance that these points move between each time and fill this in on Table 13.1. It may help to outline the dune for each image.

Table 13.1 – Dune movement distance

Time Period	Northern Point (m)	Central (m)	Southern Point (m)
1/2008-9/2009			
9/2009-6/2012			
6/2012-7/2013			
Total Movement			

- b. What is the dune movement rate for each part of the dune? The rate is distance/time. Fill this in on Table 13.2.

Table 13.2 – Rate of dune movement

Time Period	Northern Point (m/yr)	Central (m/yr)	Southern Point (m/yr)
1/2008-9/2009			
9/2009-6/2012			
6/2012-7/2013			

- c. Why do you think there are different movement rates for the dune?

- d. What is the overall movement rate for each part of the dune over the 5.5-year period?

- i. Northern Point: _____
 ii. Central: _____
 iii. Southern Point: _____

- e. How long before each part of the dune makes it to the westernmost buildings of the film set?

-
- f. **Critical Thinking:** Figure 13.5 is the latest image from the film set from 2023. What happened to the dune?

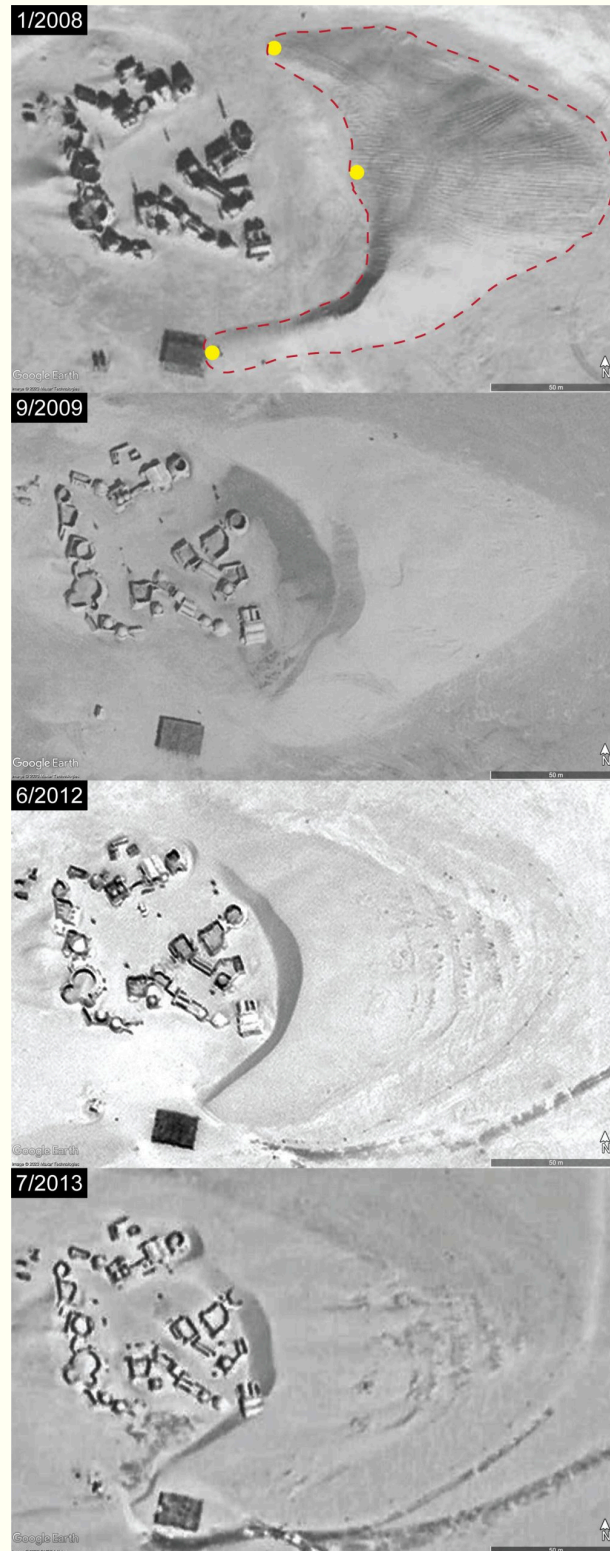


Figure 13.4 – Four images from different times over 5.5 years of a barchan dune near a film set in Tunisia. In the first image, the dune is outlined in red and three parts of the dune are indicated by yellow circles. Image credits: Google Earth, enhanced by Alex Maze.

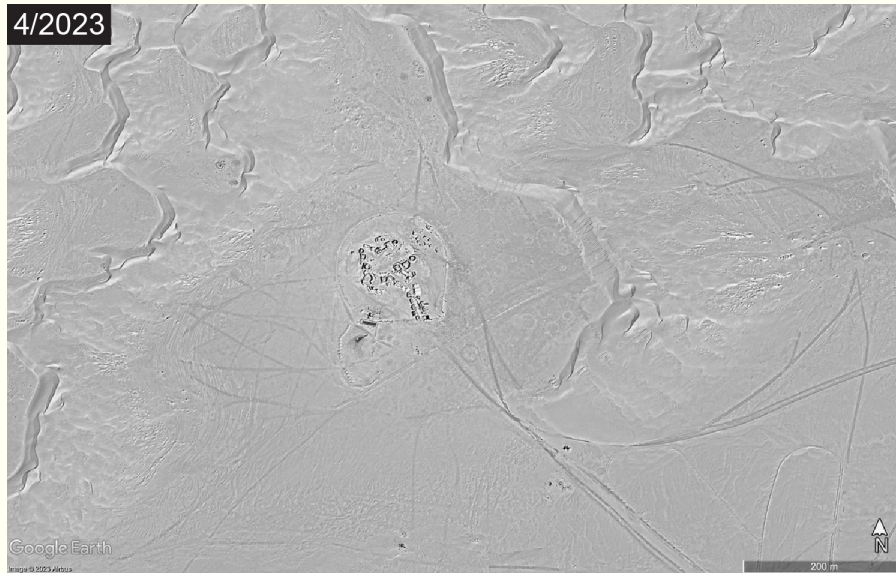


Figure 13.5 – Recent image from 2023 of the film set site in Tunisia. Image credit: Google Earth, enhanced by Alex Maze.

13.3 Glacial Landscapes

Next let's explore glacial landscapes where snow turns into dense glacial ice. A glacier is a body of ice that moves under its own weight. Currently, glacial ice covers about 10% of Earth's land surface, mainly in Antarctica and Greenland. At various times throughout geologic history, glacial ice has been much more extensive, covering up to 90% of the Earth's land surface. They are the largest repository of freshwater on Earth (~69% of all freshwater) and are highly sensitive to climate change. For mountainous regions, glaciers are an important source of drinking water.

There are two types of glaciers: alpine (found at high altitudes) and continental (found at high latitudes). The largest glaciers can cover entire continents and be several kilometers thick. Ice masses of this size leave behind very distinct features. As they advance, they carve through the surrounding landscape and transport sediment. As they retreat, large volumes of meltwater carry and deposit sediment. These carved or deposited features can tell scientists that a glacier used to cover an area and inform them about how the glacier behaved.

Many glacial features are very large, larger than what can be observed in a single outcrop. One way that geologists can interpret large-scale landscape features is through LiDAR imaging (Light Detection and Ranging). LiDAR is an imaging technique that can make a detailed elevation map of an area without tree cover.

Exercise 13.3 – Observing Glacial Landscapes

To observe some glacial features in LiDAR for yourself, first visit the [Washington LiDAR Portal](#). Once you have entered the site, select "Hide All" towards the top of the page. Then scroll down the grey list of maps until you see "Island 2014" and select the box next to DTM Hillshade. After a second, you should see a greyscale digital hillshade model covering Whidbey Island in northern Puget Sound.

- a. Look at the southern half of Whidbey Island. Describe the pattern(s) you see in the landscape. It may help to zoom in to either 2 km or 1 km on the scale bar.

- b. How do you think these patterns could have formed?

- c. What can you infer about the ice flow direction in this area?

- d. Look to the far west side of the island, just west of Penn Cove. Describe the pattern(s) you see in the landscape. Zoom in to 100 m on the scale bar for the best view.

- e. What are these features?

- f. Look at the northern part of the island, northeast of Crescent Harbor. Describe the pattern(s) you see in the landscape. Zoom to 500 m on the scale bar for the best view.

- g. Where else on the island did you see these features? What are the differences in their orientation?

- h. How would you explain the difference in orientation?

- i. Figure 13.6 shows the extent of the Puget Lobe of the Cordilleran ice sheet 16,000 years ago. Why do you think Mount Baker was not covered by the glacier?

- j. What about the area just south of Mount Baker?



Figure 13.6 – Map of the Pacific Northwest showing the location of the Puget Lobe of the Cordilleran ice sheet 16,000 years ago. It was about 5,000 feet thick at Bellingham, 3,500 feet thick at Seattle, and 2,000 feet thick at Tacoma. Image credit: Patrick T. Pringle, Washington Division of Geology and Earth Resources Information Circular 107, Public Domain.

Isostasy and Glacial Rebound

Another factor in understanding landscapes is the height of a region. In lecture, you may have been introduced to the concept of isostasy, or the principle that the Earth's crust is floating on the mantle, like a raft floating in the water. Isostasy also applies to high topography in mountainous regions. As erosion reduces the height, the weight of the crust decreases, and it rebounds. This same principle applies to glaciers, as thick glacial ice adds weight to the crust and causes the crust to subside. For example, the Greenland Ice Sheet is over 2,500 m thick, and the crust beneath the thickest part has been depressed to the point where it is below sea level over a wide area (Figure 13.7). The same is true in parts of Antarctica. When the ice sheet melts, the crust and mantle will rebound.

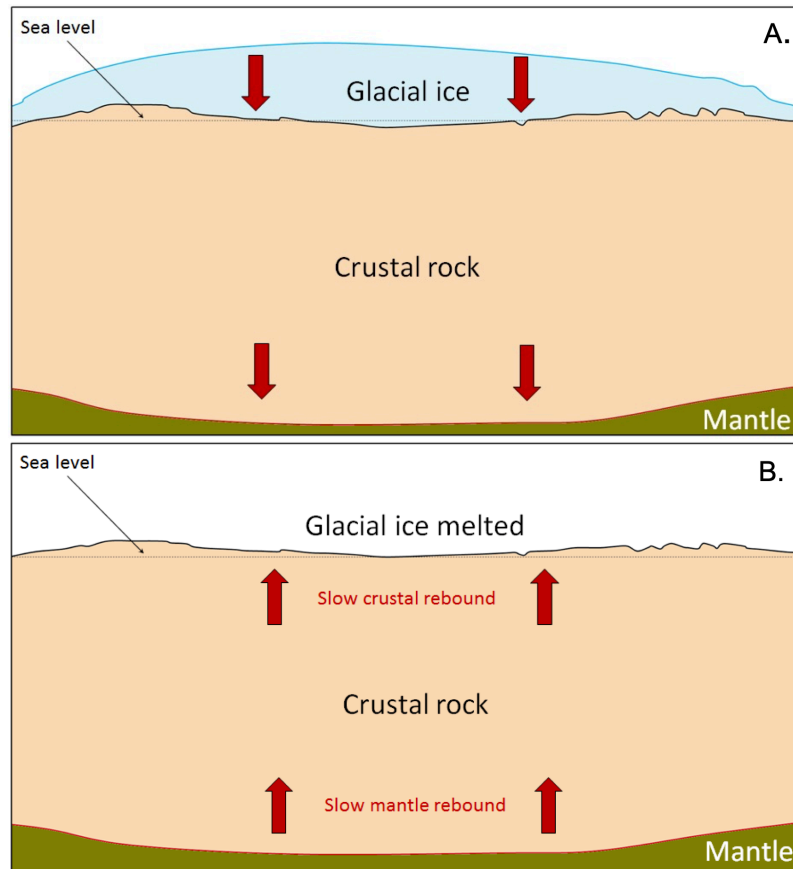


Figure 13.7 Two cross-sections through northern part of Greenland. A. Present day with ice ~2,500 m thick. The red arrows represent downward pressure on the mantle because of the mass of the ice. B. About 2,000 years into the future after complete melting of the ice sheet. Isostatic rebound shown by red arrows of the mantle would not be able to keep up with this rate of melting. So, for several thousand years the central part of Greenland might be close to sea level or even below sea level. Image credit: [Steve Earle](#), CC BY.

To measure Earth's movements, geoscientists use high precision global positioning satellites (GPS) instruments. You probably have used the GPS in your mobile phone to get you where you want to go. Most of the time, you don't have to pay attention to the vertical data from the GPS unless you are on a hike and need to know if you are the correct elevation. So, how does the GPS get elevation data? A GPS uses trilateration to find location information. This uses overlapping spheres instead of overlapping circles to determine location (Figure 13.8). In general, the more satellite data, the more precise and accurate your location will be calculated.

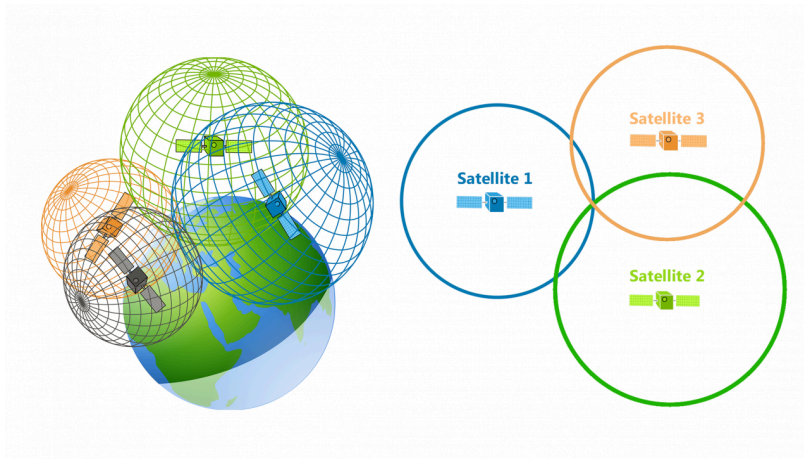


Figure 13.8 – Schematic for trilateration of four overlapping spheres for satellite locations to determine GPS position. Image credit: GISGeography used with permission.

Exercise 13.4 – Glacial Rebound

Greenland is the world’s largest island located between the Arctic and Atlantic oceans and is covered by a large ice sheet. This vast body of ice covers 1,710,000 square km (660,000 sq mi), roughly 80% of the surface of Greenland. Recent estimates are that 1,034 billion metric tons of ice was lost from 1985 to 2022. This ice has a minimal effect on sea level causing an increase of 0.5 mm. More importantly, it has introduced lots of cold and fresh water to the northern oceans (Greene et al., 2024). So, how is the landscape of Greenland reacting to this change. According to isostatic rebound theory, it should be going up. Now let’s check this hypothesis.

To confirm this, you will use GPS data to monitor glacial change, and its relationship with sea level rise. There are many GPS stations located on the island. We will use those that are continuously recording. GPS data records changes in easterly, northerly, and upward movement. For this exercise, you will only observe the upward or downward movement. Figure 13.9 shows the locations of nine different continuously monitored GPS stations that record data every 5 minutes. Figure 13.10 are time series of the data for these stations.

- a. Fill in Table 13.3 to summarize velocity at each station using the data in 13.10.

Table 13.3 Summary of Vertical Motions in Greenland

Station									
Rate									

- b. Use Figure 13.9 to show the vertical motions using the arrow as scale. This scale can only be used for data less than +/-20 mm/yr.
- c. Do any of the stations show a decrease in height? Why

d. Describe the yearly motion for one station. Why does it increase and decrease?

e. Do all areas of Greenland show the same amount of vertical motion? Explain.

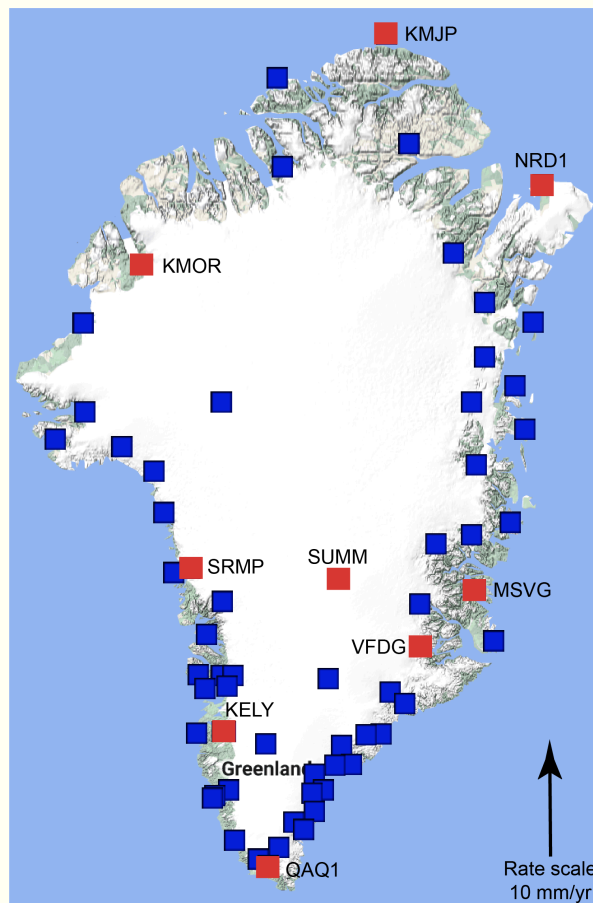


Figure 13.9 – Map of Greenland with GPS locations with red boxes for the locations used in this exercise. The arrow can be used to add rates for each location. Note: UH professor Dr. Carlson is investigating the effects of glacial retreat near the KELY station. Image credit: map adapted from Nevada Geodetic Laboratory GPS Network, Blewitt et al. (2018).

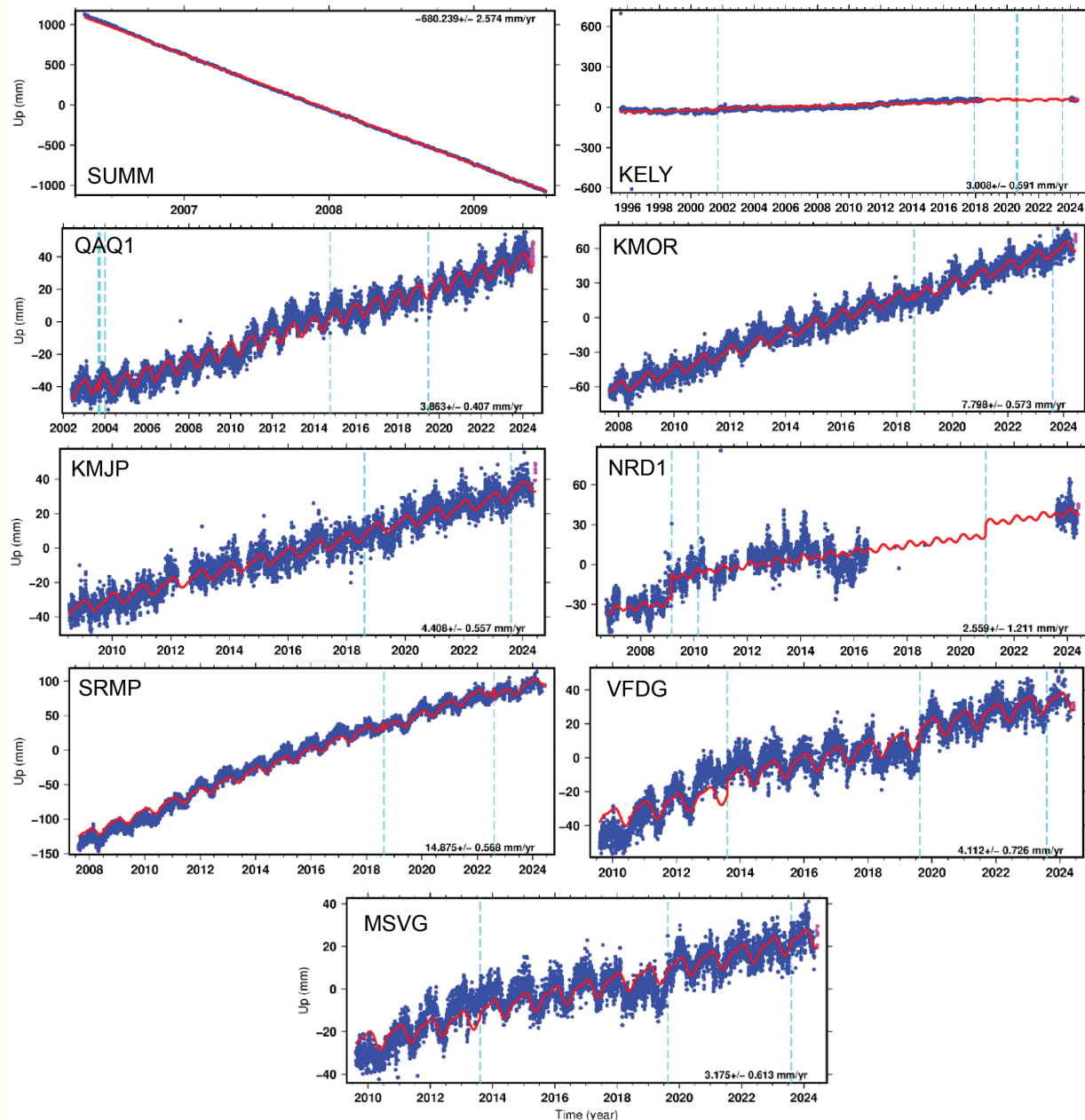


Figure 13.10 – Nine graphs of vertical motion for Greenland measured by GPS. The horizontal axis is years and vertical axis is upward motion. Each station records a different time span. The total vertical motion is also different in each plot. The blue dots are the data obtained every 5 minutes. The red line is the least squares fit to the data points. At the bottom right of every graph is the best fit estimate for vertical change in mm/yr. Dashed cyan blue lines indicate changes in the GPS equipment. Data downloaded on 7/5/2024. Image credit: graphs from Nevada Geodetic Laboratory GPS Network, Blewitt et al. (2018).

13.4 Groundwater, Karst, and Subsidence

It may not seem like an important part of the landscape, but groundwater flow controls many aspects of geomorphology underground. Caves are a geomorphic feature formed beneath the surface by dissolution of limestone. Limestone at the Earth's surface can dissolve to form karst topography. Both caves

and karst form as carbon dioxide from the atmosphere dissolves in rainwater, making the water slightly acidic. The acidic water widens existing cracks or crevices, which leads to even larger cracks and more water flow and dissolution. In addition to chemical weathering, mechanical erosion occurs as loose rock fragments transported by water erode the sides of the openings.

A critical requirement for the development of karst is water. Without water, there would be no karst or caves. On a global scale, a significant portion (15-20%) of the Earth's surface is underlain by limestone that has the potential to form karst. Therefore, understanding karst processes is important, particularly where humans interact with this landscape (Figure 13.11). Karst landscapes have features and resources that are not present in non-karst landscapes. Karst aquifers provide the main source of water; for example, 25% of US groundwater comes from karst, such as the Edwards aquifer in central Texas.

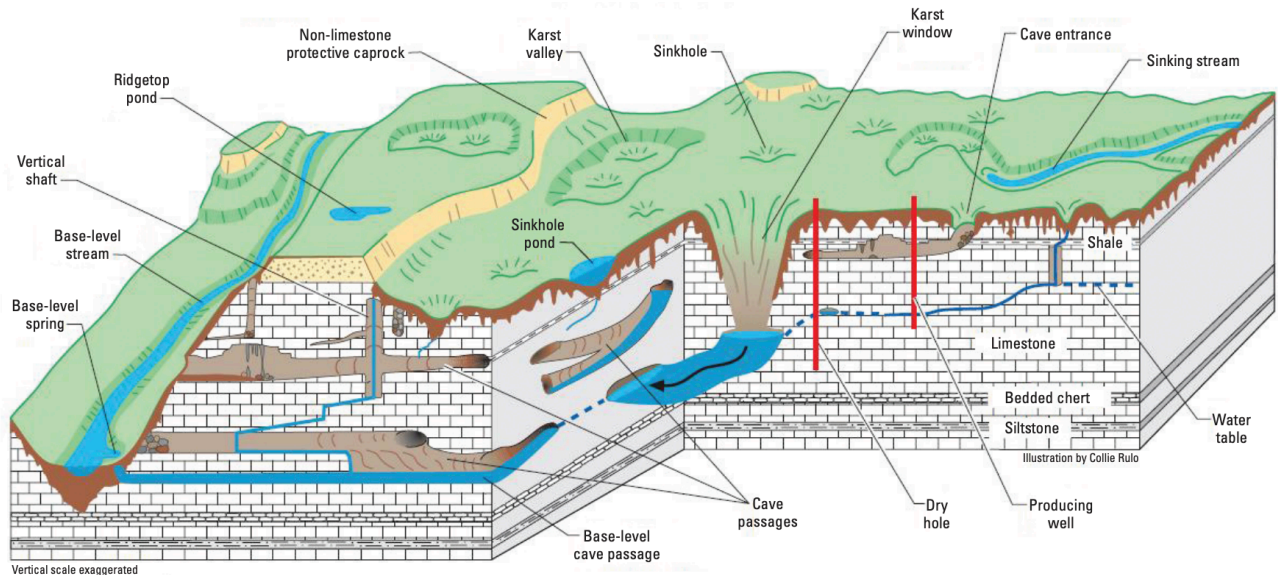


Figure 13.11 Landforms above and below ground in a karst landscape. Vertical red lines are water wells. Also shown are rivers above ground and water flow below the surface. Image credit: Taylor and Green (2008) [USGS](#), Public Domain.

Exercise 13.5 – Karst and Sinkholes

Extensive carbonate occurs in southern Virginia and northern Tennessee. In fact, there is a state park, near Clinchport VA, with a natural tunnel that is over 255 m (838 ft) long that once had a railroad running through it. Compare the satellite image (Figure 13.12) with LiDAR image of the same area (Figure 13.13) for an area east of Natural Tunnel State Park.

- Make observations about the landscape in the tree covered area in the LiDAR.

- Compare this with the farmland surrounding the wooded area. Use Figure 13.13 and name the landforms in the farmland.

-
- c. Use the geologic map and rock descriptions in Figures 13.14 and 13.15 and list the different geologic units in each area.
-

- d. **Critical thinking:** Almost every unit in this area is a type of limestone. Why is some of the area filled with sinkholes and some does not have any karst features?
-
-

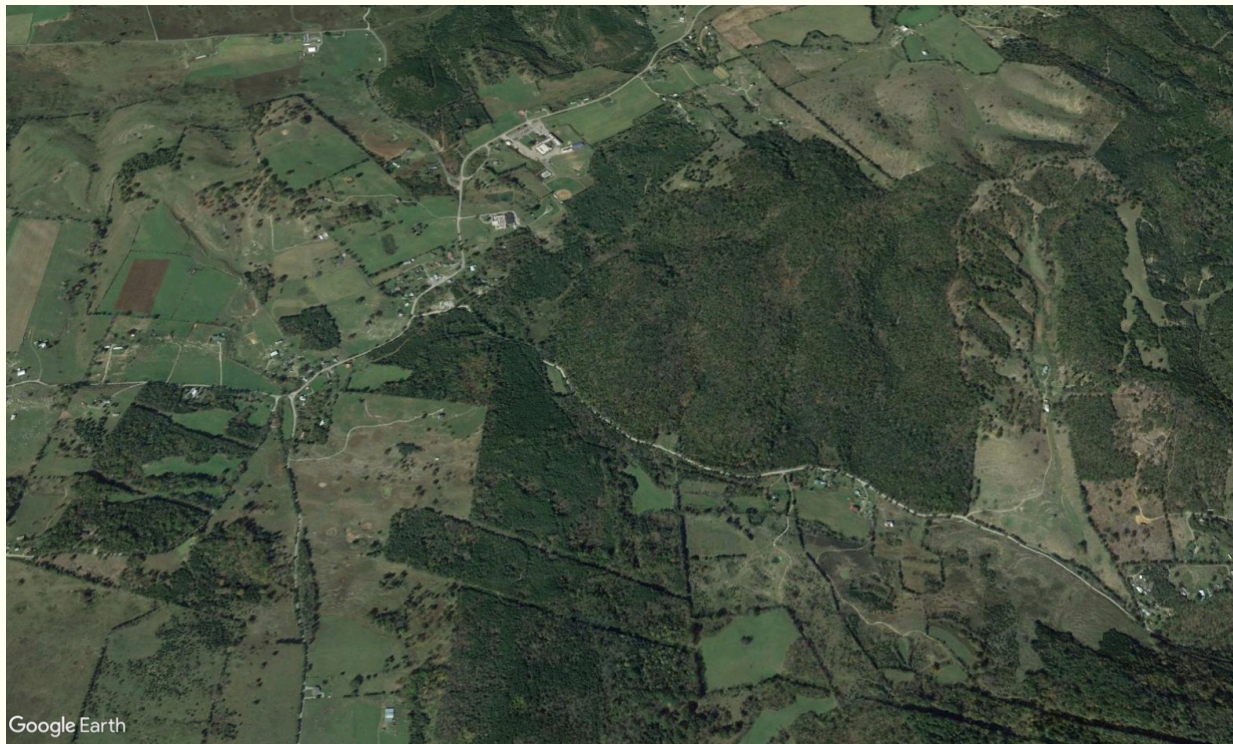


Figure 13.12 – Satellite view of region east of Natural Tunnel State Park, Virginia. Image credit: [Philip Prince](#) from Google Earth.

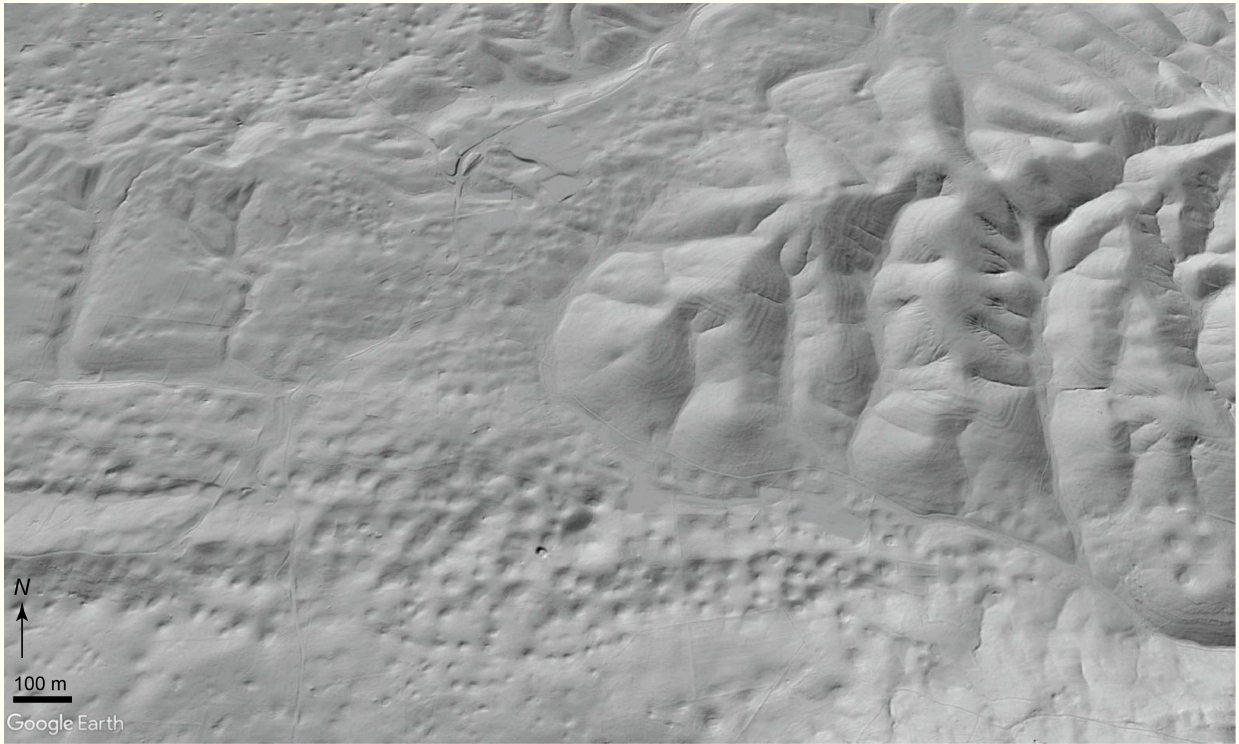


Figure 13.13 – LiDAR view of region east of Natural Tunnel State Park, Virginia. Image credit: [Philip Prince](#) CC BY.

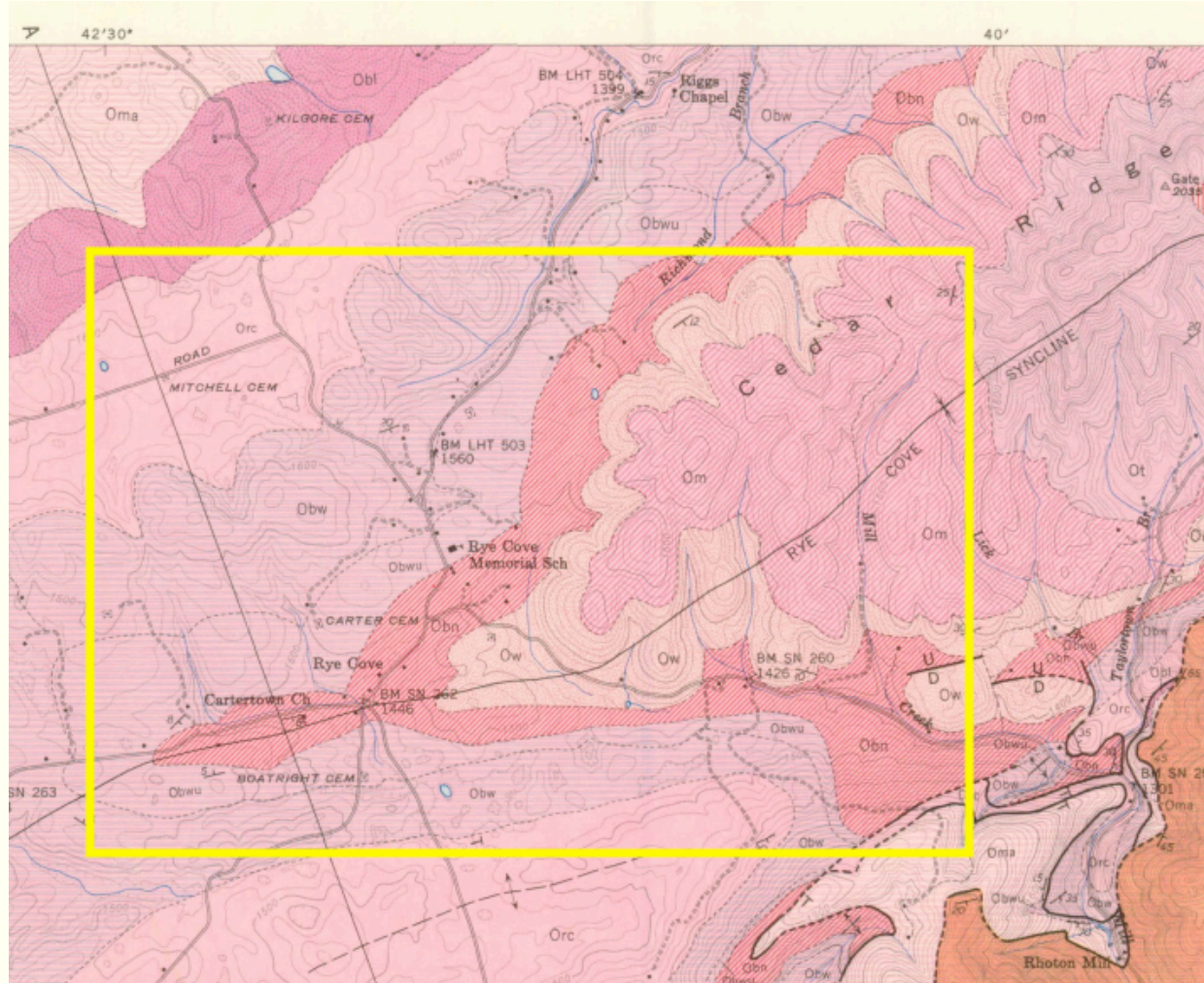


Figure 13.14 – Geologic map of region east of Natural Tunnel State Park, Virginia. Dashed lines are approximate contacts between units. Solid line with U/D is a normal fault showing which side went up versus down. Also shown is the hinge of a syncline. The yellow box outlines the area shown in Figures 13.8 and 13.9. Scale is the same as in Figure 13.8. Image credit: adapted from [Brent \(1963\)](#), Public Domain.

Age	Formation Name	Rock description	Thickness (m)
Middle Ordovician	Moccasin Fm. (Om)	Red and yellow shale and gray limestone	150-180
	Witten limestone (Ow)	Thin- to thick-bedded, fine-grained, gray limestone	55-70
	Bowen Fm. (Obn)	Red, yellow, and gray limestone and shale	15-30
	Bendolt (Obwu) and Wendell (Obw) limestones	Muddy, cobbly-weathering limestone and coarse-grained limestone, bluish chert	90-130
	Rye Cove limestone (Orc)	Dark, fine- to medium-grained, cherty limestone	60-70
	Blackford Fm. (Obl)	Dolomite, limestone, shale, basal conglomerate	25-35

Figure 13.15 – Stratigraphic section for the region near Natural Tunnel State Park giving the relative age, rock description and thickness of the units in meters. Colors for the various units approximate the colors in the map. Fm. = formation. Between the Blackford Fm. and Rye Cove limestone, some units are missing in this map area. Image credit: Virginia Sisson CC BY-NC-SA adapted from Brent (1963), Public Domain.

Both surface water and groundwater play a significant role in landscape development. Groundwater is stored in the open spaces within rocks and within unconsolidated sediments. Porosity is the percentage of open space between grains in a sediment or sedimentary rock. Some volcanic rock has a special type of porosity related to vesicles, and some limestone has extra porosity related to cavities within fossils.

Do you think water can flow through a basalt with lots of vesicles? No, as there is another parameter, permeability, which is the most important variable in groundwater. Permeability describes how easily water can flow through the rock or unconsolidated sediment and how easy it will be to extract the water for our purposes. A permeable material has a greater number of larger, well-connected pores spaces, whereas an impermeable material has fewer, smaller pores that are poorly connected. The characteristic of permeability of a geological material is quantified as the hydraulic conductivity (K) measured as centimeters per second (Figure 13.16).

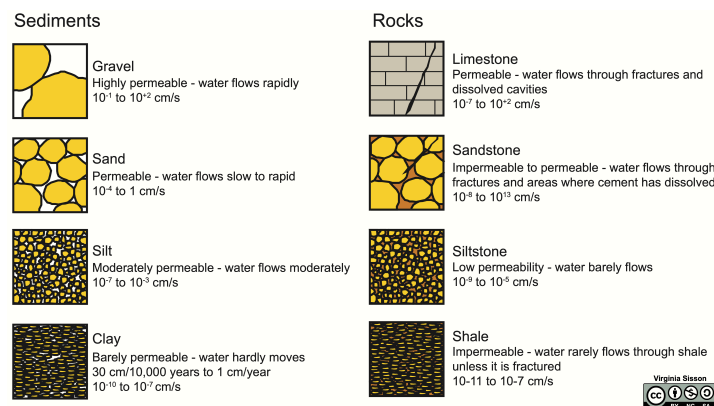


Figure 13.16 Permeability of sediments and rocks with hydraulic conductivity (K) in cm/s. Both the limestone and sandstone may have fractures which are shown as black irregular areas. Rocks are lithified with brown cement. Values for K from Freeze and Cherry (1979). Image credit: Virginia Sisson, CC BY-NC-SA.

Exercise 13.6 – Groundwater Flow – Porosity and Permeability

Let’s look at some of the factors that control groundwater flow. Your instructor will provide 3 or 4 containers with sediment with a screened bottom, similar to Figure 13.17.



Figure 13.17 – Experimental set-up for various sediments to measure permeability. Image credit Chris Calvelage CC BY-NC-SA.

- a. Pour the same amount of water into each container. Record the time it takes for the water to flow through the sediment. Fill in Table 13.4. Your instructor will determine how many trials you need to do to complete this table.

Table 13.4 – Factors affecting groundwater flow

Observation	Container 1	Container 2	Container 3	Container 4
Grain size, sorting, and rounding, and sediment type				
Time elapsed				
Flow rate (volume/ time)				
Color of water				
Volume of water retained?				

- b. Which sediment transmitted the most water? Which sediment transmitted the least water?

- c. What properties of these sediments are correlated with good water transmission? Which properties are correlated with flow retardation and water retention?

- d. **Critical thinking:** Which of these sediments will provide a clean source of water? Will any of these materials be a good filter for either organic matter or pollutants?

- e. Now take two samples of porous material – vesicular basalt and coquina and put them across a beaker. Which of these do you think is more permeable?

- f. Use an eye dropper and pour water over these two samples. Which sample allows water to pour through it? Was your hypothesis correct?

Subsidence may seem like a minor change in the landscape because, in most areas, sinking is negligible. To those living near the coast, it's a major threat combined with rising sea levels and climate change. Not only will coastal communities be affected, but their water supplies are also susceptible to an influx of salt-water. This problem makes many more vulnerable to sea level changes, such as the Mississippi Delta and [America Samoa](#). This process results in coastal retreat and land loss. In the Mississippi Delta, about 60 km²/year is vanishing. Not only is this important for those who live there, but the Atchafalaya River basin (Figure 13.18) provides flood relief for the Mississippi River, slowing its flow and trapping nutrients and pollution, improving water quality as it flows into the Gulf of Mexico.

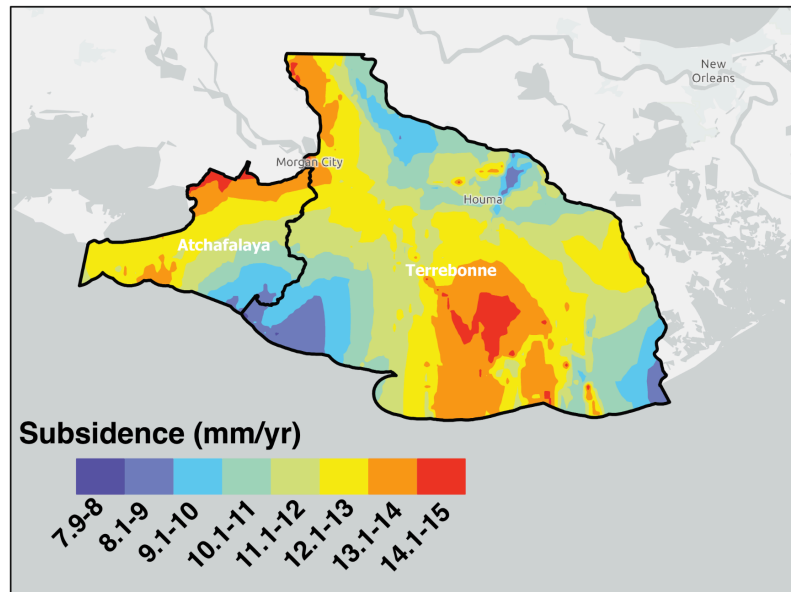


Figure 13.18 – Subsidence map for part of the Mississippi and Atchafalaya River basins. The cooler colors are low subsidence rates, and the hotter colors are the highest subsidence rates. Combine this with sea level rise, results in significant land loss which is not equally distributed. Image credit: Varugu and Jones (2023), Public Domain.

Exercise 13.7 – Groundwater Flow – Subsidence

Houstonians started pumping groundwater about 1836, and almost immediately, this began to cause subsidence, with most of the Houston-Galveston area subsiding (sinking) more than 0.3 m (~1 foot). Some areas near Baytown subsided as much as 4 m (~13 feet); an entire subdivision sunk below sea level, and it is now all marsh. In addition, before 1977, Houston aquifers (Chicot, Jasper, and Evangeline) lost ~100 m (300-400 feet). In reaction, the Texas legislature created the Houston-Galveston subsidence district in 1975. One of their first initiatives was to install a network of wells to measure groundwater and subsidence; data collection started in 1977 and continues today. Use this [link](#) for recent water well data around Houston. This will show you how water well data is made into a contour map.

- a. Figure 13.19 shows the water level in wells around Houston TX in 1977. The USGS has shown contour lines relative to sea level (0 feet). You have worked with topographic maps showing relief with contour lines that connect equal points of elevation. You can also use contour lines for other types of data. However, the USGS only contoured part of the data. Finish the contour map.

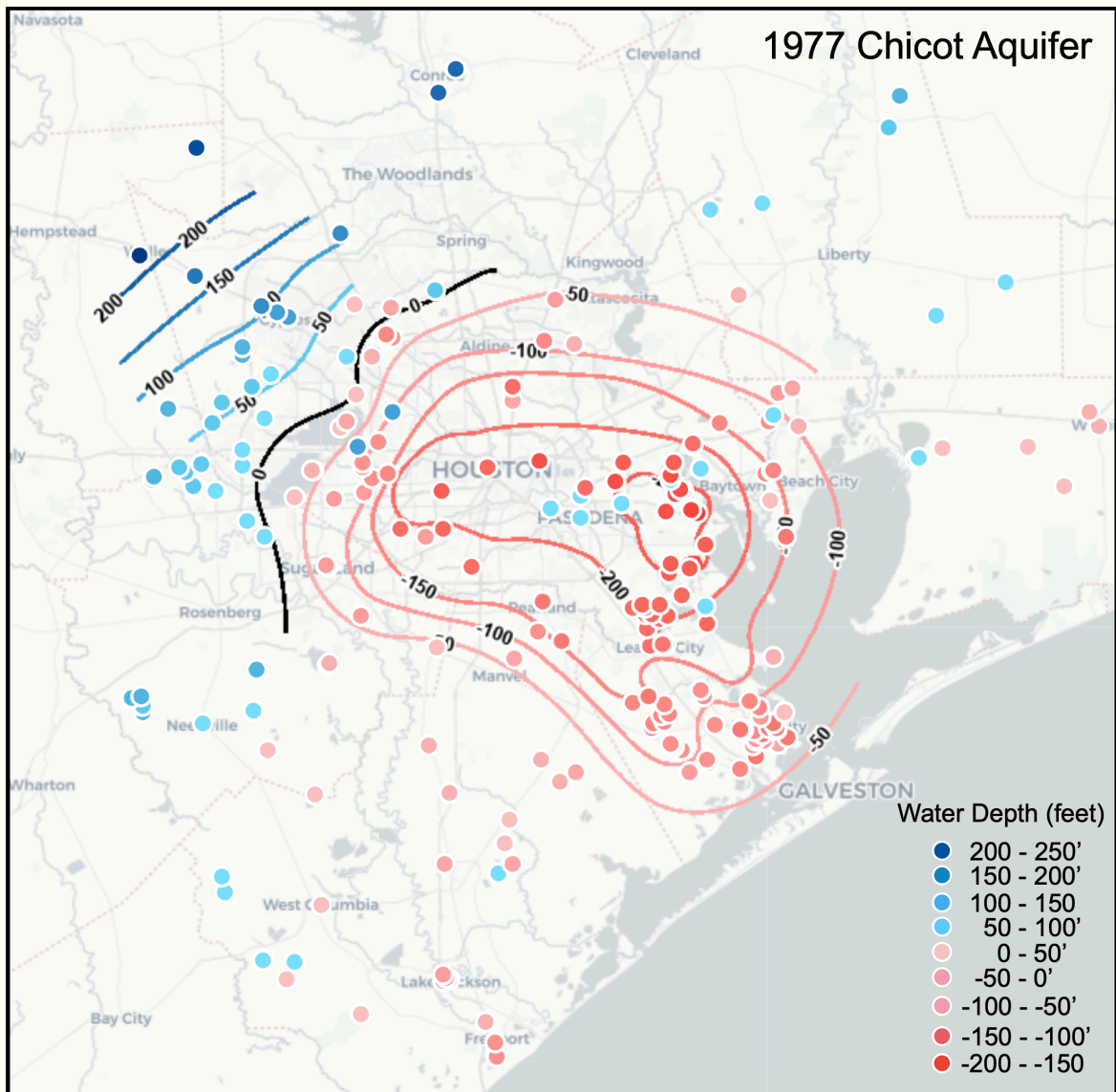


Figure 13.19 – Water well data and contours for Greater Houston area in 1977. Image credit: U.S. Geological Survey Public Domain (note this website is no longer available).

- b. When this data was collected in 1977, Houston was withdrawing ~138 million gallons of water per day, and it is now about pumping only 8 million gallons per day. How has this affected ground water levels? Compare your contour map with the map for the Houston region in 2020 (Figure 13.20).

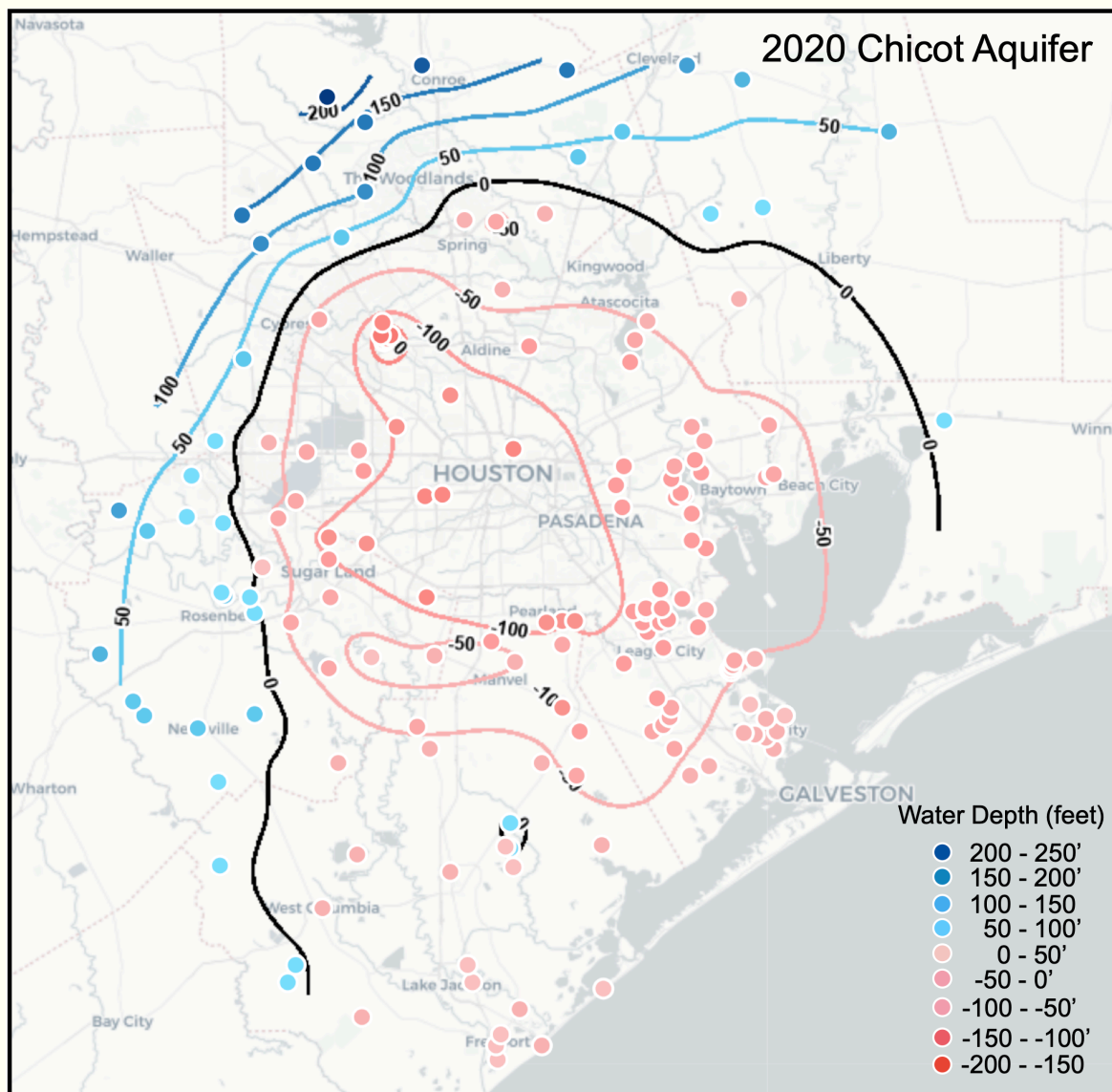


Figure 13.20 – Water well data and contours for Greater Houston area in 2020. Image credit: U.S. Geological Survey Public Domain (note this website is no longer available).

- c. Is the total range of water depths similar? Has the water level increased or decreased from 1977 to 2020?

- d. How does the sea level contour look in both maps? Has it moved relative to downtown Houston?

- e. **Critical Thinking:** Do you think that the water level will keep getting shallower through time? Or will it reach a steady-state value? Explain.

Groundwater exists everywhere there is porosity. However, whether that groundwater is able to flow depends on the permeability. An aquifer is defined as a body of rock or unconsolidated sediment that is permeable. An aquitard, or confining layer, does not allow significant water flow. Figure 13.18 shows a cross-section through the Greater Houston area with various aquifers and confining layers as well as the direction of water flow from where it enters the system in the recharge area to the discharge area.

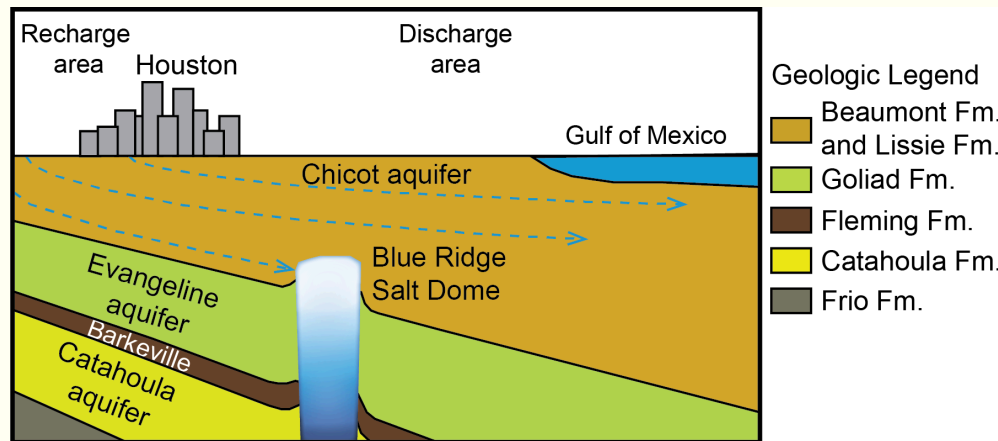


Figure 13.21 – Schematic cross-section of aquifers under Houston TX. The geologic legend shows the rock formations. Also shown is the Blue Ridge salt dome which is near Missouri City TX. The salt dome is ~70 m below the surface. Dashed blue lines are approximate paths for water flow in the aquifers. The Beaumont and Fleming Fms. are predominantly impermeable shale layers called confining layers. Image credit: Virginia Sisson CC BY-NC-SA modified from Chowdhury and Turco (2006).

- f. Next, let's compare the water level with subsidence rates in these water wells. Contour one of the subsidence maps in Figure 13.23 and compare your results to the rest of the class.
- g. Where is the most subsidence located?

- h. Are the patterns from Figure 13.23 similar to the water well contours of Figures 13.20 or 13.21? How are they different?

- i. **Critical thinking:** Even without making a contour map, you can see that the amount of subsidence

changes with time. Since groundwater withdrawal has been stopped. What other factors could explain the shifts in subsidence rates in this area?

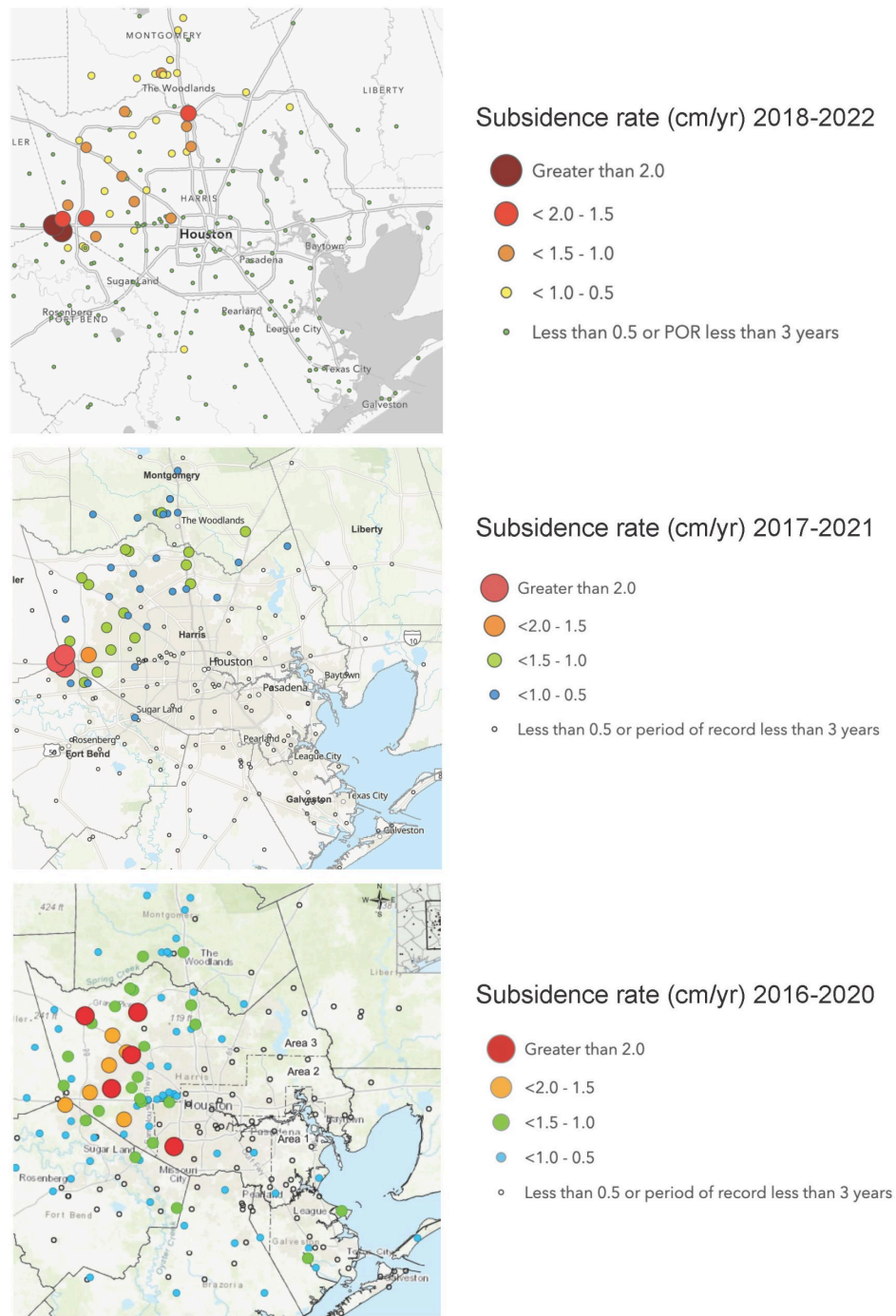


Figure 13.23 – Land subsidence rates in the Greater Houston area for three time periods. Each image covers a 5-year time period. Note that the colors for the subsidence rate are not consistent. Image credit: Aquifer Data – Harris Galveston Subsidence District (hgsubsidence.org), Public Domain.

Additional Information

Exercise Contributions

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CHAPTER 14: PLANETARY GEOLOGY

Moon, Mars, and Meteorites

Learning Objectives

The goals of this chapter are to:

- Understand the evolution of rocky planets
- Compare physical features on Earth with other planets
- Apply geologic principles of Earth on other planets

14.1 Is Geology Unique to Earth?

Recent planetary missions by NASA and other space agencies have confirmed that the geological processes you have investigated on Earth also help create and shape the rocky planets and moons. Common processes link the internal structure, landscapes, and features such as volcanoes, impact craters, ice caps, dunes, faults, rivers, and oceans. Each new mission to space reveals that many supposedly dead planetary bodies still experience eruptions, landslides, and dust storms. Moreover, our understanding of the Solar System has increased by studying meteorites from asteroids and Mars and rock samples collected on the Moon.

14.2 Meteorites

At the beginning of the semester, you may have gone over the history of the solar system and how the planets were formed. Some of the evidence for what the early solar system was like and the structure of the Earth comes from meteorites because they are fragments of the early solar system. There are three types of meteorites: stony, iron, and stony-iron. So, how do you identify these? They are typically dense, possibly magnetic, have unusual shapes, sometimes with pits, and often have a “fusion crust” that forms when the meteorite falls through the atmosphere. Many possible meteorites are rocks, minerals, or slag left over from making steel.

- Stony meteorites are composed of silicates and other materials. Most stony meteorites also contain both iron and nickel metal. These are the most common type; 94% of all meteorites are stony.
- Iron meteorites are composed of iron (Fe), nickel (Ni), and sometimes cobalt (Co) and other trace elements and minerals. Iron is the predominant metal with a variable ratio of iron to nickel.
- Stony-irons are a combination of iron and stony meteorite properties and are the rarest type of meteorite. Pallasites are simply spectacular stony-irons. In a polished slice, you can see iron-nickel metal surrounding olivine crystals.

As of June 2024, 2,823 confirmed meteorites have been collected in the United States according to [The Meteoritical Society](#), mostly in arid regions of states. In Texas, 322 have been found, and, recently, some were lucky enough to witness a meteorite fall near Brownsville, TX on Feb 12, 2023. Six days later meteorite hunters found pieces near El Sauz, TX.

Exercise 14.1 – Meteorites and Internal Structure of Rocky Planets and Planetesimals

Figure 14.1 shows three different types of meteorites. Typically, any meteorite with metal is made into a polished slab (Fig 14.1 A and D)

- a. Which of these is from the core of a planetesimal?

- b. Which represents crustal material?

- c. Which represents the core-mantle boundary?

- d. **Critical Thinking:** What do the materials (metal, stony-metal, and stony) imply about the early processes of planet formation in terms of planetary structure? (hint: recall that oil and water do not mix but have a meniscus between them.) Do you think that silicate and metal liquids mix or not? Explain.



Figure 14.1 Five meteorites found in Texas. A and B are iron meteorites with A as a polished slab and B unpolished piece; C is a cut slab of an aubrite; D and E are the same pallasite meteorite with D as a polished slab and E unpolished piece. Image credits: all images from [Meteoritical Bulletin Database](#) with A. Iron IIIAB found in Davis Mountains in 1903, photo by [Don Edwards](#), ~ 1 cm across; B. Iron IIAB found in Iredell TX in 1898 photo by [Don Edwards](#), ~1 cm across; C. Aubrite found in Pena Blanca Spring, Brewster Co TX in 1946, photo by [Peter Marmet](#), ~3 cm across; D. Pallasite found in Sterley TX in 1950, photo by [KD Meteorites](#), ~9 cm across; E. unpolished slab of pallasite found in Sterley TX in 1950, photo by [L. Garvie](#), ~12 cm across.

14.3 Martian Rock Cycle

Rocky planets (or terrestrial planets) are relatively small compared to the Gas Giants. Rocky planets have solid surfaces, often pockmarked by impact craters. These don't have rings, and they have few or no moons. They may have evidence of past or current tectonic and volcanic activity. On Earth, the rock cycle explains how the three rock types relate to each other and how they change over time. We've spent a lot of time talking about the rocks on Earth, but do other planets have rock cycles?

Mars, sometimes called the Red Planet, is the fourth planet from the Sun (Figure 14.2). Mars has some Earth-type characteristics, such as polar ice caps, mountains, sand dunes, and clouds. It is the planet most visited by spacecraft in our solar system. As of 2024, 21 lander missions and 8 sub-landers (rovers and penetrators) attempted to land on Mars. Of 21 landers, the Curiosity and Perseverance rovers are currently still in operation. Curiosity rover has long outlived its expected mission as it has been roaming the surface of Mars for over 11 years!

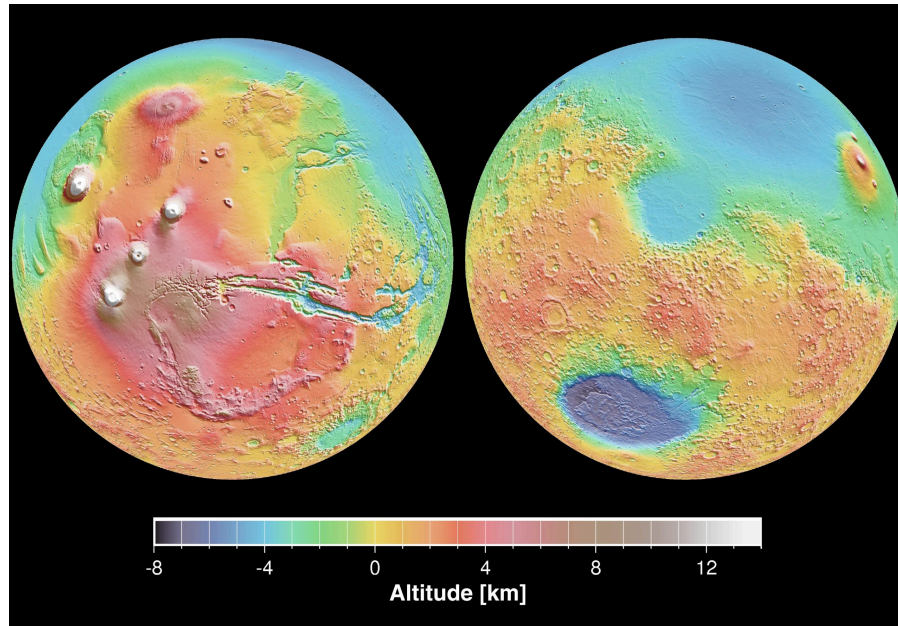


Figure 14.2 – Global false-color topographic views of Mars from the Mars Orbiter Laser Altimeter (MOLA). The vertical accuracy is less than 5 meters. The right-hand image view features the Hellas impact basin (in purple) and Elysium Mons (isolated white region). The left-hand features the Tharsis topographic rise (in red and white) and Valles Marineris (linear blue region): Image Credit: [NASA](#) Public Domain

Exercise 14.2 – Martian Rock Cycle

Today, Mars is no longer volcanically or tectonically active. However, remnants of Mars' massive volcanoes remain (Figure 14.3). Its most recent eruption is estimated to have occurred only 50,000 years ago near Elysium Mons. In fact, some attribute recent Mars quakes to movement of magmas. To distinguish features on planets from those on Earth, mountains are called Mons (singular) or Montes (plural).

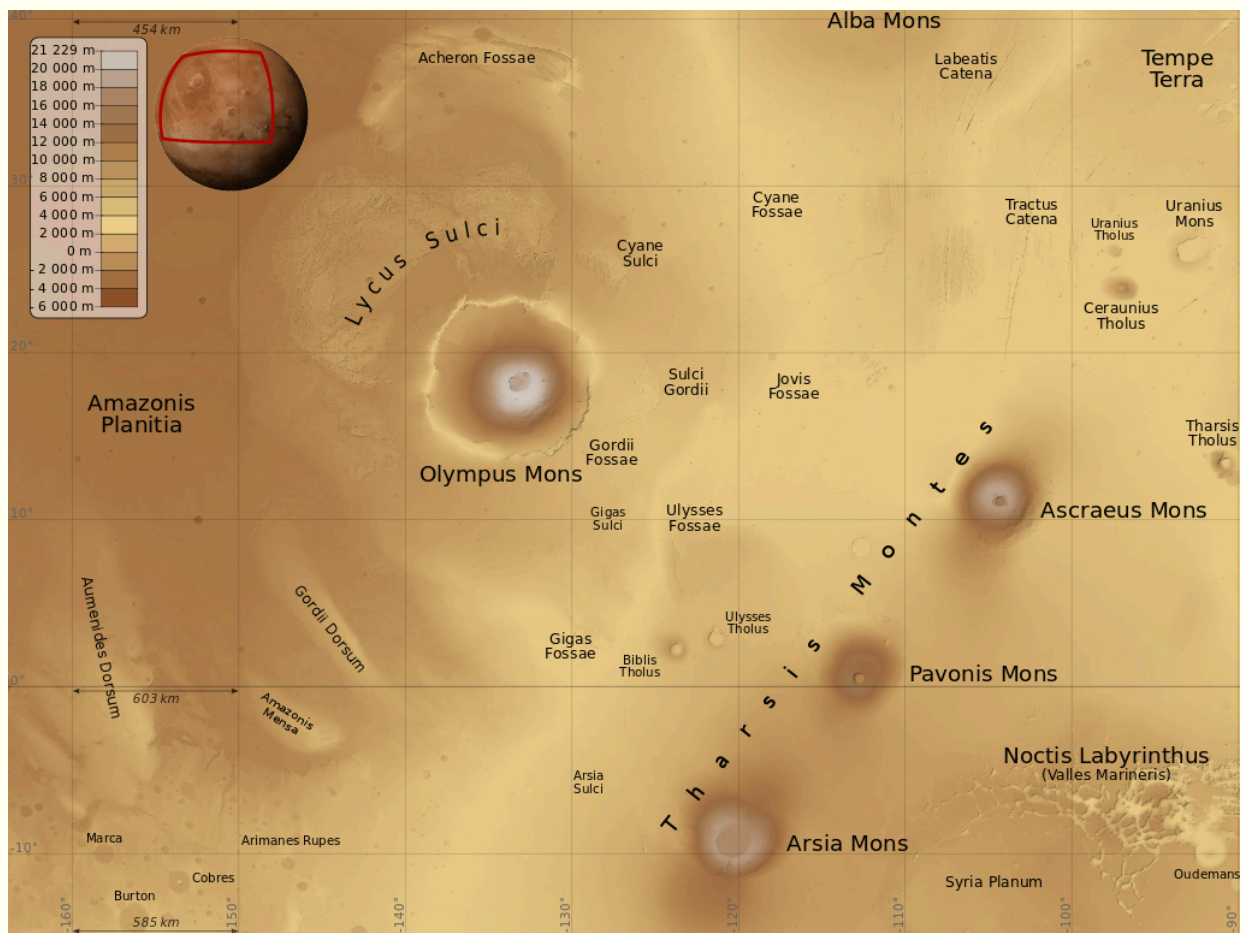


Figure 14.3 – Map of Olympus Mons and Tharsis Montes region on Mars. Image credit: [Sémhur](#), CC BY-SA.

- a. Tharsis Montes are three enormous volcanoes located within the Tharsis region of Mars. These volcanoes form a straight line each other and align with other volcanoes in the region such as Ceraunius Tholus and Uranus Mons. What does this chain of volcanoes in the Tharsis region suggest about volcanic and tectonic history of this region?

- b. Figure 14.4 is a picture of an igneous rock taken by NASA's Curiosity Mars rover. The light-colored, elongated crystals are likely feldspar; some are 1 cm in size. The dark-colored matrix surrounding the feldspar is pyroxene.
 - i. Describe the texture and cooling history of the rock.

- ii. Is this rock felsic, intermediate, mafic, or ultramafic? How can you tell?

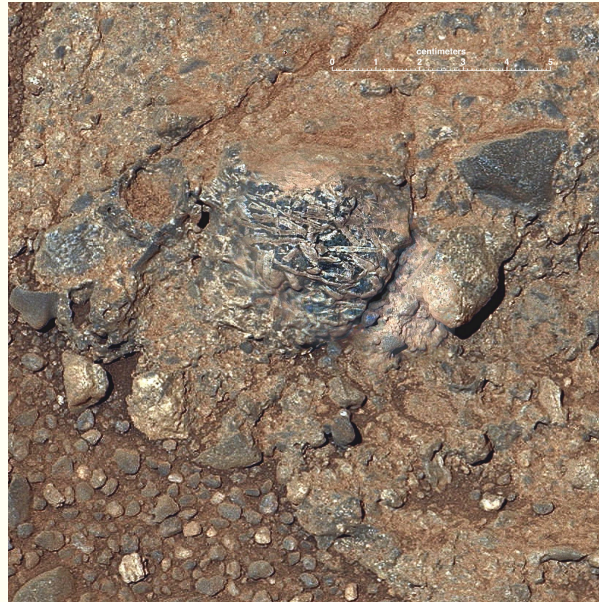


Figure 14.4 – Martian rock ‘Harrison’ from inside Gale crater on the lower slope of Mount Sharp. Created by merging images from two cameras on NASA’s Curiosity Mars rover. Annotated figure includes a scale bar in the upper right. Image credit, [NASA](#), Public Domain.

- c. Figure 14.5 is a picture of a sedimentary rock taken by NASA’s Curiosity rover.

- i. Describe the texture of the rock.

- ii. How much energy is needed to transport the pebbles?

- iii. Today, the main mechanism for sediment transport on Mars is wind. What features do you see that either support or don’t support this method of sediment transport?

iv. If this rock were from Earth, what type of environment would you find it?

v. What does this imply about Mars's geologic history?

vi. At present, could there be water on Mars?



Figure 14.5 Martian outcrop 'Link' imaged by NASA's Curiosity rover. Annotated with a scale bar on the lower right. Image credit: NASA JPL-Caltech/MSSS, Public Domain.

d. Do you think we could find metamorphic rocks on Mars? Use Figures 14.6 to help.

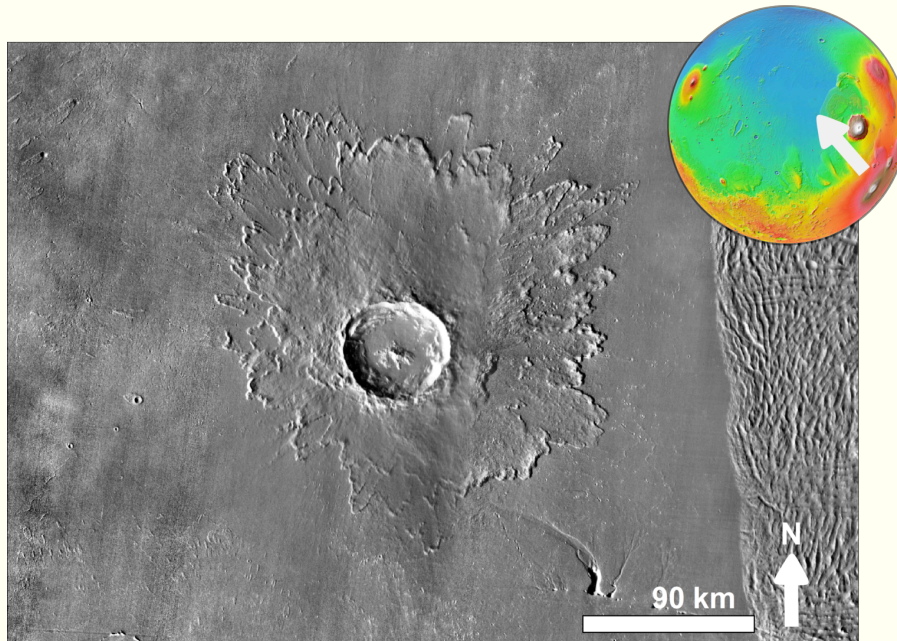


Figure 14.6 – A photo of Tooting crater on Mars. Inset shows location of crater to the west of Olympus Mons. Crater is at 23.1°N, 207.1°E, in Amazonis Planitia. This crater is estimated to be one of the youngest on Mars formed at ~1.1 Ma. Image credit: NASA, modified by [Chmee2](#), Public Domain.

- e. Meteorites also hold clues about metamorphism of our solar system and Mars. Figure 14.7 shows two different meteorites from Mars; one which originated from Mars during an impact about 700,000 to 1.1 million years ago and another which fell to the surface of Mars. Both of these images record possible metamorphic changes. Can you identify these processes?

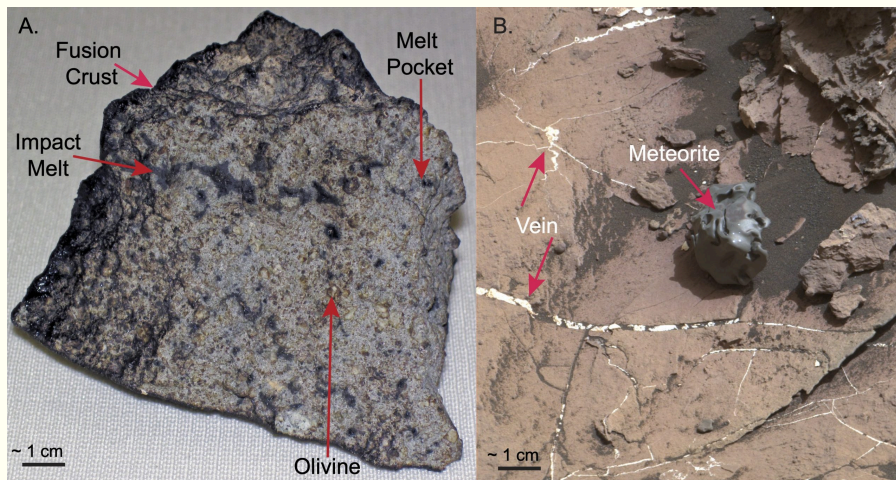


Figure 14.7 – Two photos of Martian meteorites. A. Tissint meteorite that witnesses watched fall onto the Moroccan desert. B. Curiosity rover has discovered several meteorites on the surface of Mars including “Egg Rock”. Several small white pits show where the rover analyzed the rock confirming it is an iron-nickel meteorite. Also, there are abundant white veins made of calcium sulfate (anhydrite, bassanite, and perhaps gypsum). Image credit: A: [James St. John](#), CC BY; B: [NASA](#), Public Domain.

- f. Another way to investigate planetary surfaces is to use satellites equipped with spectrometers such as CRISM (Compact Reconnaissance Imaging Spectrometer for Mars). CRISM uses detectors that see in visible, infrared and near-infrared wavelengths to map the minerals that have water in their structure. This spectrometer surveyed the surface of Mars from March 2006 until January 2023. Figure 14.8 shows a geologic map of the Terra Sirenum region with relative ages based on impact relationships. Also shown are some of the CRISM results showing mineral locations for both minerals in igneous rocks (primary minerals) as well as secondary minerals formed by either metamorphism, hydrothermal activity or evaporite (lake systems).

- i. Look at the distribution of primary minerals. Do they occur only in impact craters? What is their age?

- ii. Look at the distribution of secondary minerals. Do they occur only in impact craters? What is their age?

- iii. The presence of gypsum (a common variety of polyhydrated sulfate) may indicate evaporite deposits. Do these occur only in impact craters? What is their age?

- iv. **Critical thinking:** According to Viviano et al. (2023), this region has 30% more secondary minerals than other areas on Mars. Why do you think this area has more secondary minerals?
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-

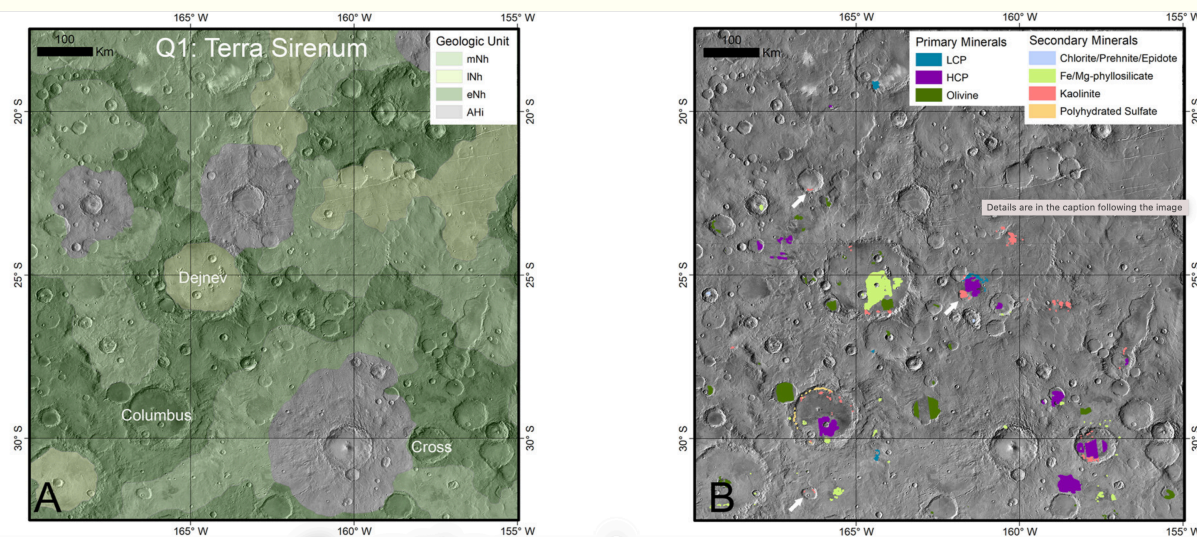


Figure 14.8 Geologic map and mineral map in the Terra Sirenum region of Mars which is southwest of Arsia Mons (Figure 14.3). In part A, geologic units are Amazonian-Hesperian impact (AHi) 3.7 Ga to present, and Noachian (mNh, middle Noachian highlands, lNh, late Noachian highlands, eNh, early Noachian highlands) 4.1 to 3.7 Ga. These relative ages are from Tanaka et al. (2014). In part B, primary minerals indicate the presence of mafic igneous rocks with olivine and pyroxene (low calcium LCP and high calcium HCP). Secondary minerals include metamorphic chlorite, prehnite, epidote, mica (biotite), clay (kaolinite) and gypsum (polyhydrated sulfate). White arrows indicate a new discovery of kaolinite identified recently using CRISM data. Image Credit: Viviano et al. (2023), CC BY.

Exercise 14.3 – Lunar Geology

Other planets and moons have shown evidence of geologic activity, like Earth's moon. Head to this interactive map of the [Moon](#) created from images with the Lunar Reconnaissance Orbiter Camera.

- a. Separate the moon's surface into different types using any criteria. What are the criteria you used and why?
-
-

- b. Share your criteria with the class and compare answers.

Hopefully, you picked up on the distinction between two different colors on the Moon's surface: a lighter shade of white or gray and darker colored areas. The lighter areas are the lunar highlands and are composed

of anorthosite, a special type of granite with mostly calcium-rich feldspar. The darker areas are the lunar mare or maria, composed of a special type of basalt called KREEP, which has high concentrations of potassium (K), rare-earth elements (REE), and phosphorus (P).

- c. Describe the distribution of craters on the moon. Is there any distinction between the highlands and the maria?

- d. You may have heard about recent attempts to land on the South Pole of the moon with two failed missions from Japan and Russia and two successful missions including India's Chandrayaan-3 and the short-lived Odysseus mission by Houston based Intuitive Machines . NASA has proposed that the first Artemis III flight land in this region in 2026. Describe the landscape in this region. Why is there renewed interest in landing in this region?

- e. **Critical Thinking:** Some areas of the moon have more craters than others. Why? Note: Under the layers tab > ACT Layers, turn on TerrainHillshade to really see the difference.

14.4 Relative Dating in the Solar System

There are thousands of craters on the moon, Mars, and other planets, and only ~190 on Earth. Planetary scientists use the law of superposition with these craters to determine the relative ages of the moon and other planets. As you found out in Chapter 10 on geologic time, cross-cutting relationships is a principle in geology used to decipher the relative ages of rocks and geologic features. This principle is based on the concept that a rock or feature must be younger than any rock or feature it cuts across. We can apply this principle to determine the relative ages of features on other planetary bodies. For example, the surface of Mercury has many landforms, including ridges (rupes) and craters. Figure 14.7 shows that the ridges may be younger than some craters yet older than others. Some craters even cross-cut other craters!

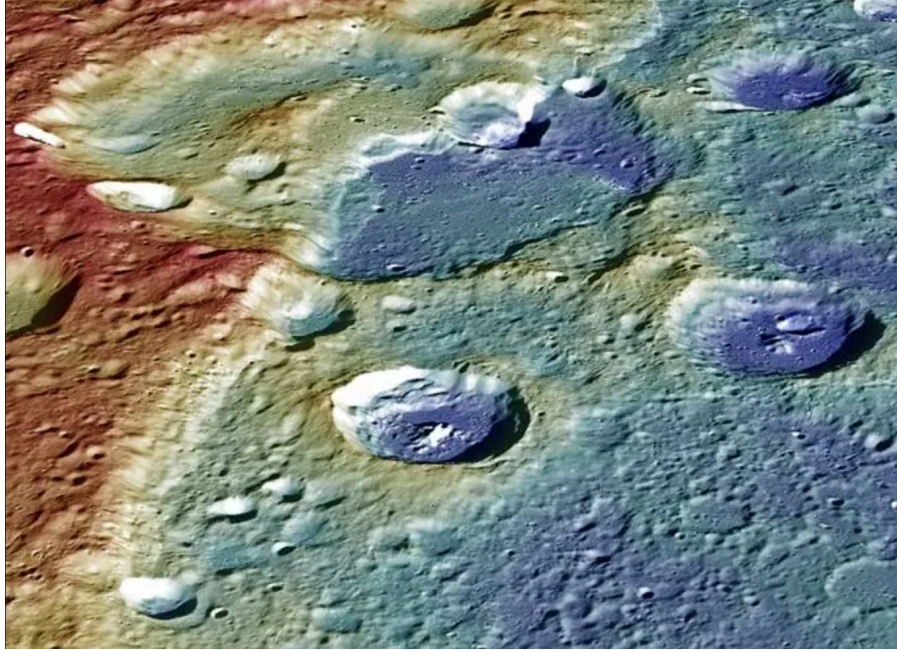


Figure 14.9 – A false-color image of Mercury showing Carnegie Rupes (ridge), a large tectonic landform, which cuts through Duccio crater. Image credit: [NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington](#), Public Domain.

Exercise 14.4 – Relative Dating on Mars

Figure 14.10 is a Google Earth image from Mars that shows craters, fractures, and river channels. Use the principle of cross-cutting relationships to answer the following questions.

- a. Which is older, Crater A or Fracture A? How can you tell?

- b. Which is older, Crater A or Channel A? How can you tell?

- c. Is Crater B younger or older than Crater A? How can you tell?

- d. If Fracture B cuts through Channel A, is Crater A younger or older than Crater C?

- e. Look at Figure 14.11. Arrange five of these craters in relative order from oldest to youngest.

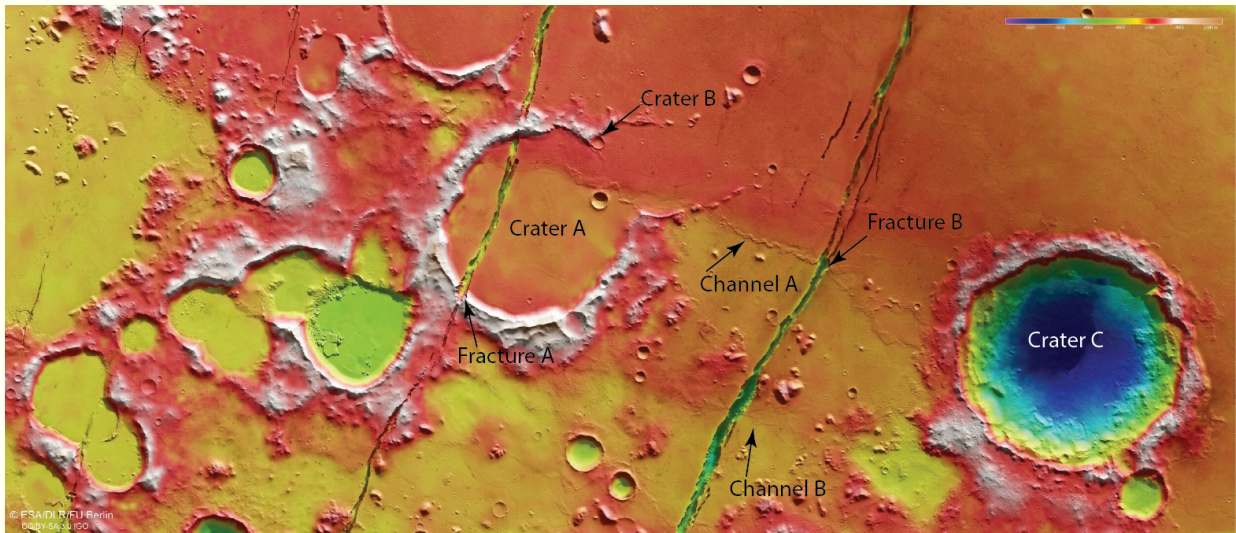


Figure 14.10 – Topographic image from Mars of Cerberus Fossae. The fossae – meaning ‘ditches’ or ‘trenches’ in Latin – stretch for more than 1000 kilometers. Color coded topography with reds and whites relatively higher than blues and purples (see key at top right for values). Approximate coordinates are 10°N, 159°E. Image credit: adapted from [European Space Agency ESA/DLR/FU Berlin](#), CC BY-SA.

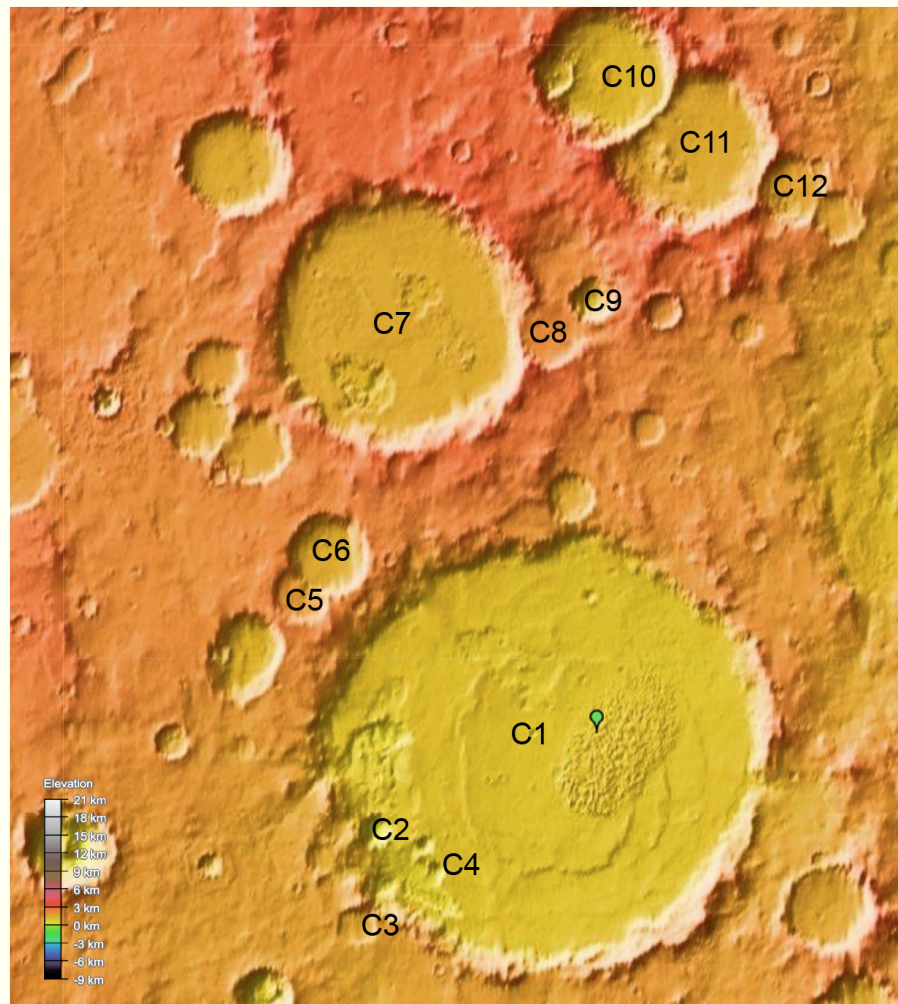


Figure 14.11 – Topographic image from Mars of Proctor Crater (C1) with labels for various craters. Color scale for elevation at lower left with yellow at 0 km and reds are ~3 km high. Crater C1 is at 47.5oS, 30.2oE. The green pin in Proctor Crater indicates a dune field. Image credit: adapted from Google Mars.

14.5 Planetary Dunes

As you learned in the landscape chapter, dunes are classified by the amount of sand and wind direction. On Earth, vegetation also influences dune morphology, but vegetation is not an issue in the rest of the solar system. The sand that makes up planetary dunes is just small solid particles, which can be basaltic or even solid methane if you are in the outer solar system. Planetary geologists have identified dunes on Earth, Venus, Mars, Titan (moon of Saturn), Triton (moon of Neptune), Io (moon of Jupiter), Pluto, and at least one comet.

Exercise 14.5 – Winds and Dunes on Mars

In this exercise, you'll look at some images of dunes on Mars (Figure 14.2). To interpret these, look for shad-

ows on the dunes. This is the steep versus gentle slope on the dune. The steep side will be the downwind side for barchan, transverse, barchanoid, and star dunes. When looking at these images, you must ignore the features that are not dunes, such as hills, mesas, buttes, craters, etc.

- Figure 14.12 shows several dunes from Mars. On each image, use arrows to show the direction(s) of the wind. Also mark a spot where you might land to explore this region.
- For each image, determine the dune type, number of wind directions, and relative amount of sediment. Fill in this information in Table 14.1.

Table 14.1 – Martian Dune Data

Location	Dune type(s)	# of wind directions	Sediment amount
A. Summer dunes (43° N)			
B. Dunes in crater (12° S)			
C. Winter Dunes (76° N)			
D. Chasma Boreale (85° N)			

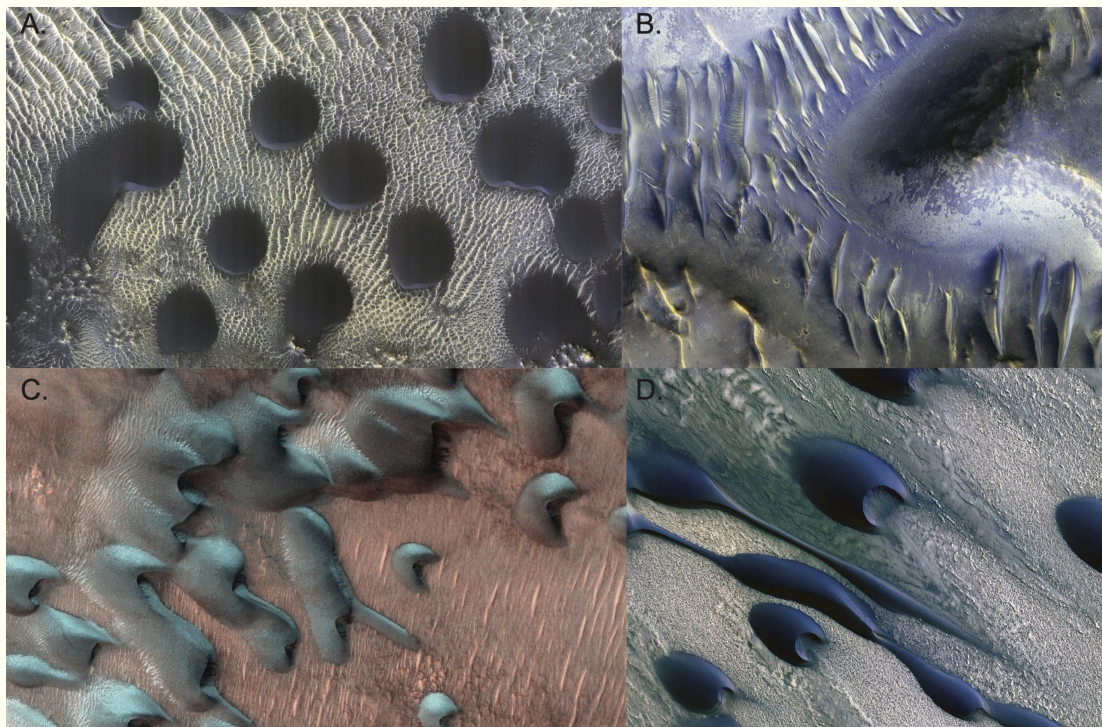


Figure 14.2 – Four false-color images of Martian dunes. A. Dunes sitting on white ridges of gypsum that are deposited on basalt. B. Dunes formed within an impact crater with mound in the center that appears to have blocked the wind. C. Dunes with frost. Image collected on Martian winter solstice (7/22/22). This frost is mixture of carbon dioxide and water ice. D. Dunes on Mars from the north polar ice cap in the Chasma Boreale region. The white areas show irregular polygonal patterns developed in carbon dioxide ice (dry ice). The dunes are made of basalt and gypsum grains. Image credit: False-color HiRISE image from NASA/JPL-Caltech/UA/Arizona Public domain.

- Now that you've analyzed dunes from several places on Mars, let's see if you make any generalizations about winds and sediment supply on the Mars. Do these all places have only one direction of wind.

- d. Does the number of wind directions change with distance from the Martian equator?

- e. Is the sediment supply the same in the different Martian examples? Rank them from most to least amount of sediment.

- f. **Critical Thinking:** Which of these dunes fields is where you would like to go explore? Just choose one and explain why you chose that place.

Additional Information

Exercise Contributions

Virgina Sisson, Kaitlin Thomas, and Daniel Hauptvogel

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CHAPTER 15: CLIMATE CHANGE

Causes, Effects, and Solutions

Learning Objectives

The goals of this chapter are to:

- Understand geologic factors in climate change
- Interpret affects of climate change
- Evaluate a possible geologic solution to climate change

15.1 What Affects Earth's Climate?

Most of us worry about climate change as it may affect our lives and those of future generations. Geological records show that there have been a number of large variations in the Earth's climate (Table 15.1). These have been caused by many natural factors, including changes in the sun, emissions from volcanoes, plate tectonics, variations in Earth's orbit, and levels of greenhouse gases such as methane and carbon dioxide. The way these interact with each other makes it complicated. A change in any one of these can lead to enhanced or reduced changes in the others. Also, natural global climate change typically occurs very slowly, over thousands or millions of years.

Table 15.1 – Geological Factors affecting Climate

Factor	Temperature Rise or Fall	Length of time
Plate Tectonics	Rise or fall	Millions years
Volcanic Emissions	release CO ₂ – Rise release SO ₂ – Fall	Days to years
Meteorite Impacts	Fall	Decades
Earth's Orbit	Rise or fall	Thousands to millions
Sun (sun spots)	No affect	11 years

Exercise 15.1 – How Plate Tectonics Affects Climate Change

On long timescales like millions of years, plate tectonics and the position of the continents drastically affect the climate on Earth. Figure 15.1 is a map that shows glacial deposits and geomorphological features that have been identified in the red-shaded regions. These features are about 300 Ma. The black arrows show a general paleo-ice-flow direction based on field data. Though it is believed ice flowed over Antarctica during

this time, paleo-ice flow cannot be determined because of the overriding ice present on the continent today. Answer the questions below based on the map and your knowledge of the climate on Earth.

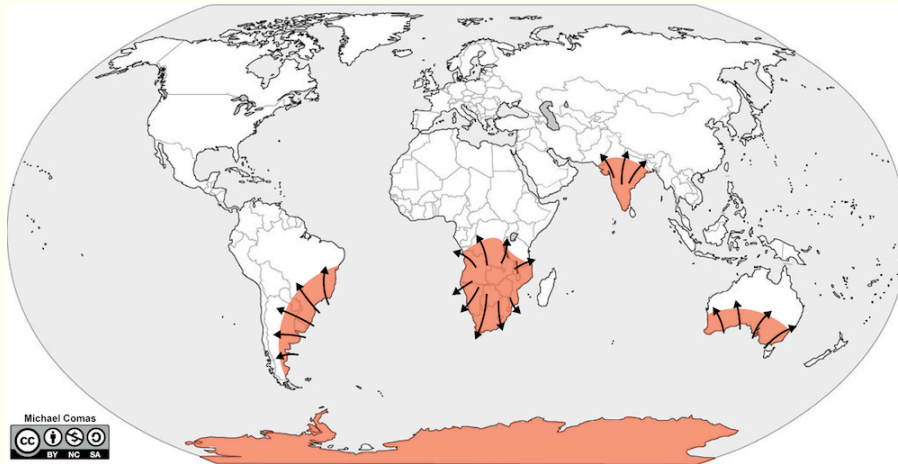


Figure 15.1 – Map of Earth showing regions with evidence of 300 Ma glaciation shaded in red. Black arrows denote the dominant paleo-ice-flow direction inferred from geomorphological data. Image Credit: Michael Comas, CC BY-NC-SA.

- a. Are any of these shaded regions known for supporting large, continental glaciers today? Why or why not?

- b. What do each of the shaded regions have in common geographically?

- c. Where are ice sheets on Earth located today? Why are they able to last there?

- d. Do glaciers typically flow from sea to land? How do you explain why glaciers appear to have done this?

- e. Now that you have thought critically about the map, give a brief explanation for why we see glacial signatures in these regions today.

-
-
- f. Where do you think the paleo-south pole may have been relative to these continents at the time of glaciation? Why? Mark this position on the map with a star.

-
-
- g. Draw a line across the present-day continents showing an estimated position of the equator during this glaciation.
- h. Do you think these areas may become glaciated again?

-
-
- i. **Critical Thinking:** How do you think Earth differs when there isn't a land mass at the poles?
-
-

15.2 Glaciers

Did you know that Earth hasn't always had glaciated polar regions? Earth goes through periods of time when glaciers do and do not exist as its climate changes naturally. In fact, twice in the past, almost every continent was covered in ice during periods geologists call "Snowball Earth." Our current phase of glaciation began about 34 Ma, and before that, you have to go back to 250 Ma to see the last time ice was present on the planet.

You already looked at landforms left behind by glaciers, now let's explore the effect of climate on glaciers. You'll look at alpine glaciers (sometimes called valley glaciers) that originate high up in the mountains, mostly in temperate and polar regions but also in tropical regions in high mountains (e.g. Mount Kilimanjaro in Africa). As these glaciers form, ice builds up where the temperatures are low, then ice begins to flow down-slope with the help of meltwater and sediment, and finally melts when the temperatures are too warm. The flow of alpine glaciers is driven by gravity.

Alpine glaciers grow due to accumulation of snow over time. In the zone of accumulation, the rate of snowfall is greater than the rate of melting. In other words, not all of the snow that falls melts during the following summer. In the zone of ablation, the rate of melting exceeds accumulation. The equilibrium line marks the boundary between the zones of accumulation (above) and ablation (below).

What factors other than gravity control the rate of glacial advance and retreat? Obviously, temperature is important. Also, there must be enough moisture to make snow. Both of these are affected by climate change. News reports have highlighted pictures of receding glaciers such as Figure 15.2. Did you realize

that by the year 2100, that over 30% or ~49 trillion metric tons of glacial ice is predicted to melt. Overall, this means ~70% of glaciers will disappear.

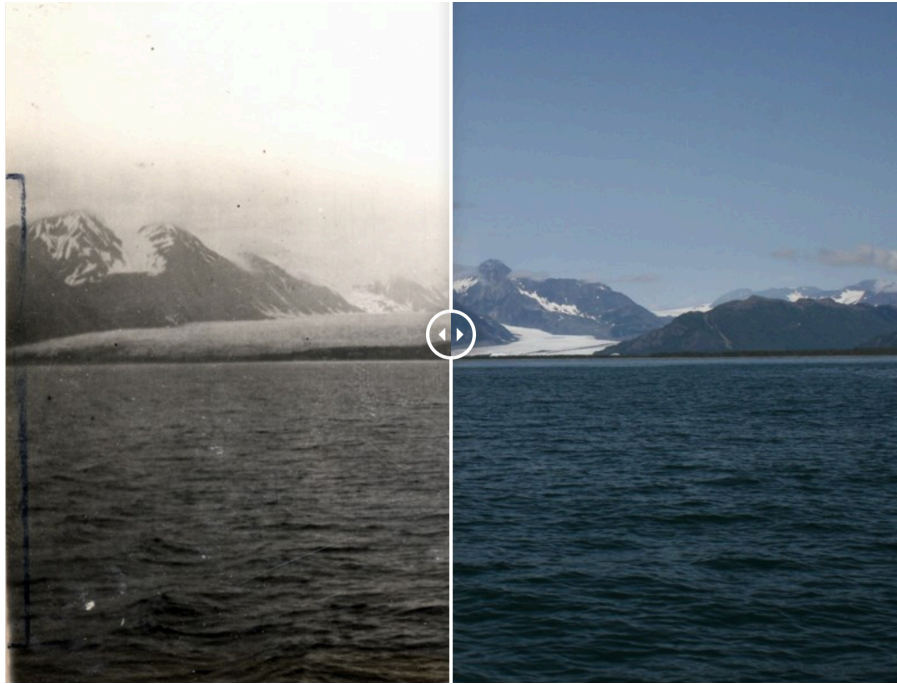


Figure 15.2 – Comparison of Bear glacier in 1909 and 2021 showing its retreat. Despite this retreat, this glacier is still the longest glacier in Kenai Fjords National Park, Alaska. It currently ends in a proglacial lake separated from the ocean by a narrow beach made by a glacial moraine. These two images show both retreat of the glacial terminus and thinning of the glacier. This [link](#) will let you move the slider to compare the two images and estimate the glacial retreat. Image credit: [US National Park Service](#) Public Domain.

Exercise 15.2 – Glacial Advance and Retreat

Visit the [glacier simulator](#) to visualize these processes in action. Upon opening the page, familiarize yourself with the parameters you can adjust. If you're struggling to see the model, uncheck the snowfall box to remove the white haze.

- a. What happens to the glacier's length when you turn the average snowfall all the way up?

- b. What happens when you turn the average snowfall all the way down?

- c. Reset the model. Hold these parameters steady for about 30 seconds. The small black dots represent

sediment sediment transported by the glacier. Where is all the sediment deposited?

- d. Now, reduce the average snowfall from 3.1 ft to 3.0 ft to make the glacier retreat slightly. Can you still identify the previous position of the ice?

- e. Turn the sea-level air temperature all the way up. When you increase the average snowfall, what happens to the glacier? Why do you think that is?

- f. Move the drill tool to the glacier and push on the red button to simulate taking an ice core from the glacier. Try moving it over the zone of accumulation as well as the zone of ablation. What do you notice about the drill hole over time? Why does this happen?

- g. Check the equilibrium line, which will create a red dashed line at a certain elevation. Use the glacial budget tool (green box) to record the glacial budget at four points along the glacier. Two points should be above the line, and two points should be below. You'll see three values: accumulation, ablation, and glacial budget. Describe what you observe about the glacial budget and what the equilibrium line means.

- h. Use the "Advanced" tab. Pause the simulation. Select the glacier length vs. time box and move the popup out of the way. This graph shows how far the glacier will advance or retreat over time. Set the temperature and snowfall parameters for maximum glacial growth and unpause the simulation. When the glacier length reaches 225,000 ft, pause the simulation and set the temperature and snowfall parameters for maximum retreat. Unpause the simulation.

i. How many years did it take for the glacier to grow to 225,000 ft? _____

ii. How many years did it take to fully collapse? _____

iii. What does this tell you about glacial stability?

i. Look at Figure 15.3 which measures the distance in miles for the retreat of Bear glacier.

i. How does this graph compare with theoretical curve you made for question h?

ii. Do you think climate has been steady or changing in Alaska? Explain.

iii. **Critical thinking:** Another factor in this glacial system is the proglacial lake. Occasionally, the beach that dams the lake breaks creating a massive flood (jökahlaup). This allows ocean water which is both salty and somewhat warmer to flow into this lake and also also experience tides. How will each of these three factors affect glacial retreat?

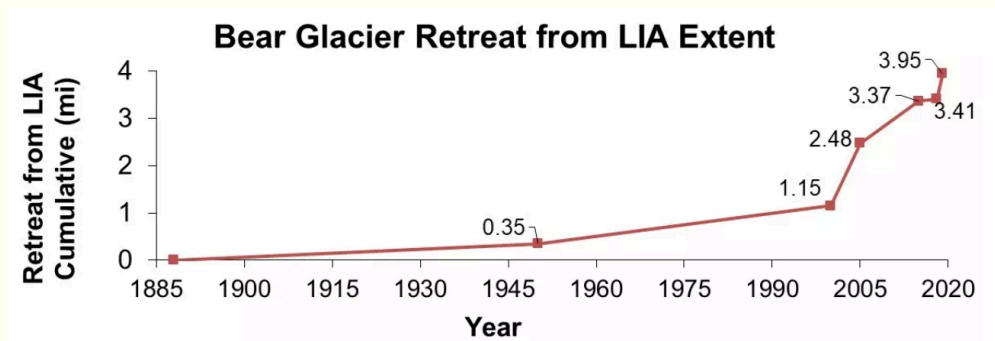


Figure 15.3 – Measured retreat of Bear Glacier in Kenai Fiords National Park, Alaska. The maximum extent of the glacier was in 1888 or the end of the Little Ice Age (LIA). Image credit: US National Park Service, Public Domain.

15.3 Sea Ice

Sea ice is different from glaciers. Sea ice is a thin layer of frozen ocean, (Figure 15.4) and as you know glaciers are ice masses on land. Since sea ice freezes at about -2°C , it is a sensitive indicator of the ocean temperature. Every year, sea ice forms at each pole; this is a very important event for a number of envi-

ronmental processes. Sea ice development supports krill populations (the base of the marine food chain), provides passages for certain animals to migrate, increases albedo (the amount of the sun's energy that is reflected back into space), and helps to drive global ocean circulation. In the Arctic, Russia's Arctic and Antarctic Research Institute has compiled ice charts since 1933. Today, scientists studying trends ice in the Arctic Sea can rely on a fairly comprehensive record dating back to 1953. To gauge what how much sea ice covered the Arctic Sea before then, scientists use a combination of historical records and proxy measurements such as marine sediment cores. Taken together, these records indicate that the ice covering the Arctic Sea is undergoing an unprecedented decline in the last several centuries.



Figure 15.4 – Photo of ice covering the Arctic Sea in the winter.
Image Credit: [Eric Røgeher](#), Public Domain.

Exercise 15.3 – Sea Ice

The [National Snow and Ice Data Center](#) has tracked the area of sea ice in the Arctic and Antarctic since 1979. Use this data to answer the following questions.

- Hide all data and select the plot for 2023. What can you say about the seasonality of sea ice in the Arctic?

- What is the approximate difference in sea ice extent (in millions of km²) between the peak and trough of 2023?

- Still looking only at the 2023 plot, what can you say about long-term trends in sea ice formation over

time?

- d. Now turn on the 2012 plot as well. With these two data sets, what can you say about trends in sea ice formation over the decade?

- e. What do you think may have been some possible causes of the anomalously low sea ice in 2012?

- f. As the site says, 2012 had record low sea ice in the Arctic. Do you think using 2012 data to compare to other years might be biasing our data? Why or why not?

- g. Turn off the 2012 and 2023 plots. Now select the four decadal averages. What can you say about sea ice trends in the Arctic over the last half-century?

- h. **Critical Thinking:** How do you think this may affect the global economy? Which countries do you think may be most closely watching sea ice levels in the Arctic?

15.4 Sea Level

Let's look at how climate has been changing recently. There are many factors in climate change that are attributed to our atmospheric inputs. Figure 15.5 shows how each different factor has affected climate. This includes natural and manmade changes.

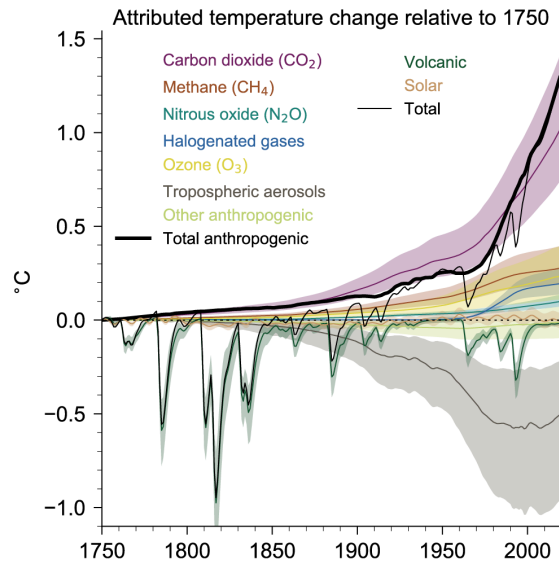


Figure 15.5 – Relationship between temperature and time covering the industrial era. Each data type has a different color line with shaded uncertainty bands. The bold black line is the total of all the different factors. Image Credit: [IPCC Sixth Assessment Report, 2021](#) CC BY-NC-ND.

How can we recognize this overall temperature increase in the geologic record and how does this affect geologic processes? Well, sea-level rise is one of the simplest to understand the cause and effects of climate change. Rising sea level is mostly due to a combination of melt water from glaciers and ice sheets and thermal expansion of seawater as it warms. In 2022, global mean sea level was 101.2 millimeters (4 inches) above 1993 levels, making it the highest annual average in the recent record (1993-present).

Exercise 15.3 – Sea-Level Rise and Coastal Erosion

In 1999, the Cape Hatteras Lighthouse in North Carolina was moved from the original position it was built in 1870 (Figure 15.6). Upon its completion, the lighthouse was an estimated 450 meters away from the coast-line. Even in 1870, strong storm surges brought seawater to the base of the lighthouse. Following over a century of sea level rise that resulted in even more intense surges, it was determined that to preserve the lighthouse, it should be moved further inland where storms would have less effect on the foundation of the structure. Answer the questions below about the Cape Hatteras Lighthouse and its relationship to sea-level rise.

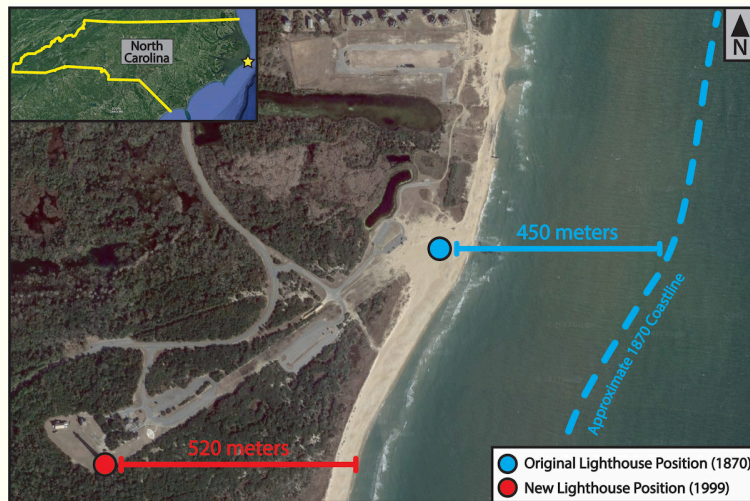


Figure 15.6 – Map showing the original position of the Cape Hatteras Lighthouse in 1870 (blue dot) and its current position (red dot). The position of the coastline in 1870 is also shown (blue dashed line). Image Credit: base map from Google Earth, adapted by Michael Comas, CC BY-NC-SA.

- a. According to the National Oceanic and Atmospheric Association (NOAA), the pace of sea level rise through most of the 20th century was 1.4 mm/yr. Using this pace, how much has sea level risen since the lighthouse's construction in 1870?

- b. If the lighthouse was approximately 450 meters from the coastline when it was built in 1870, and its old position is now ~50 meters from the coast. At what rate (in m/yr) did the shoreline advance onto Hatteras Island?

- c. Are you surprised by the distance the shoreline encroached compared to the amount of sea level rise? Explain.

- d. What do your answers say about the slope of the shorefront?

- e. Do you think this shoreline slope is representative of shorelines around the world? Why or why not?

-
-
- f. Sea-level rise estimates from 2014-2023 put the current pace at 4.77 mm/yr. In 1999, the lighthouse was moved approximately 520 meters inland, how long would it take for the sea to reach this new position of the lighthouse? Assume a constant rate of rise and the same shorefront slope.
-
-

- g. Why do you think the rate of sea level rise has increased so dramatically?
-
-

- h. **Critical Thinking:** Predictions of future sea-level rise over the coming centuries are highly variable but are expected to increase steadily. What do you think this means for the future of coastal communities and ecosystems?
-
-

15.5 Climate Change Mitigation

The term mitigation means to reduce the effects of something. Can your knowledge of geologic processes help solve recent climate change? Yes, is the simple answer. You may have heard the acronym CCUS for Carbon Capture, Utilization, and Storage which are methods and technologies to remove CO₂ from the atmosphere, followed by recycling the CO₂ for utilization as well as permanent storage options. This is not a new idea as it was first proposed in 1977 and CO₂ capture started back in the 1920's. One major energy company has captured 120 million metric tons of CO₂ accounting for approximately 40 percent of all the anthropogenic CO₂ that has ever been captured. Most of this captured CO₂ is being used for enhanced oil recovery.

What else can be done? Two other proposed solutions are either injecting captured CO₂ into the ground or into saline aquifers. To accomplish this, geologic insight is necessary. Deep saline aquifers have the largest identified storage potential, with an estimated storage capacity to store CO₂ emissions for at least a century. The captured CO₂ can be injected into sedimentary basins below depths where the temperature exceeds 31.1 °C. Why? Well, it relies on two fundamental chemical properties – supercritical fluids and immiscibility. Supercritical fluids are neither a gas or liquid; for CO₂ this occurs at temperatures above 31.1 °C. The other is immiscibility, which is like oil and water in salad dressing – they don't mix. The same is true for salty water and CO₂ when it is a supercritical fluid. Also, for this exercise, you need to understand aquifers, so you may want to review your results for exercises 13.6 and 13.7.

Exercise 15.4 – Carbon Capture

First let's explore, the relationship between permeability and immiscible liquids. Since your lab classroom is below 31.1 °C, we can't use CO₂ for this demonstration. Your TA will hand out demo bottles with glass marbles that represent sand grains and one filled with one liquid and the other filled with two immiscible liquids of different density. Your bottle may have either oil and water or water and alcohol. Food coloring has been added to make it easier to see the water. Turn these upside down and observe what happens. Then flip them back upside right.

- a. Bottle A – Record your observations:

- b. Bottle B – Record your observations:

- c. Aquitards or seals are natural barriers to fluid flow. In sedimentary rocks, these are impermeable rocks such as shale. Which one of these two bottles has an aquitard? Explain.

Modeling carbon storage in western Canada yields a conservative estimate that this area has the capacity to store 56 gigatons of CO₂, but could be as high as 360 gigatons (Hares et al., 2022). To put this number into perspective, the conservative estimate of 56 gigatons, would be ~10-13% of the current CO₂ budget. To help you visualize this, it is equivalent to all the CO₂ emitted by producing plastic for the next 25 years. Still don't have a good grasp of how much this is equivalent to, the amount of CO₂ emitted to make one single polyester shirt is somewhere between 3.8 and 7.1 kilograms, which is a lot shirts worth of CO₂ that could be stored underground in western Canada!

Now let's look at some of the local geology to figure out where to they propose to put all of this CO₂. It needs to go into an aquifer that is beneath the supercritical temperature for CO₂. Look at Figures 15.7 and 15.8 to help decide where all of this CO₂ will be injected into a saline aquifer. Geoscientists use different conventions for stratigraphic versus cross-section data. Stratigraphic data is given the depth from the surface whereas the cross-section gives elevation above and below sea level.

- d. First convert the elevation for the supercritical point for CO₂ into depth. What is the shallowest depth in a well that will be above the supercritical point? What is the deepest depth?

- e. Some of these aquifers are too shallow as they would not have supercritical CO₂. Which aquifers are too shallow and are above the supercritical point for CO₂ storage?

- f. Which of the other aquifers do you think would be good for CO₂ storage? Of these, predict which would be the best target and why?

- g. Currently, there are two operational sites in western Canada that are injecting CO₂ into the Cambrian aquifers. First is [Aquistore](#) in Saskatchewan, injecting CO₂ produced at the SaskPower carbon capture facility down to a depth of 3.4 km. The second is [Shell Quest](#) in Alberta, which captures CO₂ produced from converting tar sands into gas, transporting the CO₂ for 65 km and then injecting it to a depth of ~2.0 km. Considering these two projects, which do you think is more successful?

- h. **Critical thinking:** What additional information would you need to predict which would be the best aquifer for CO₂ storage?

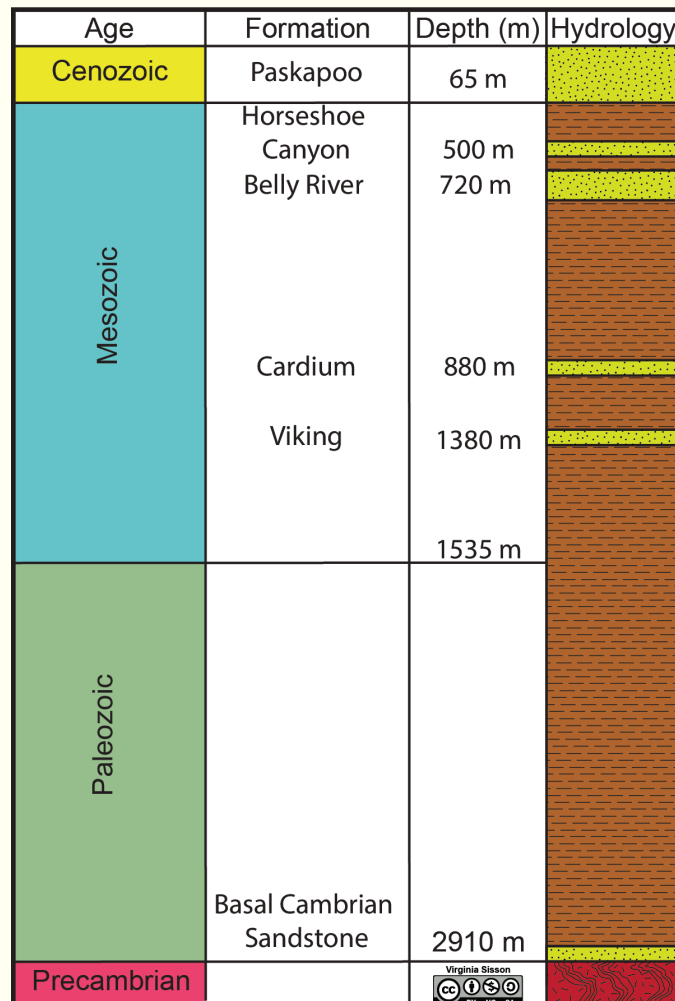
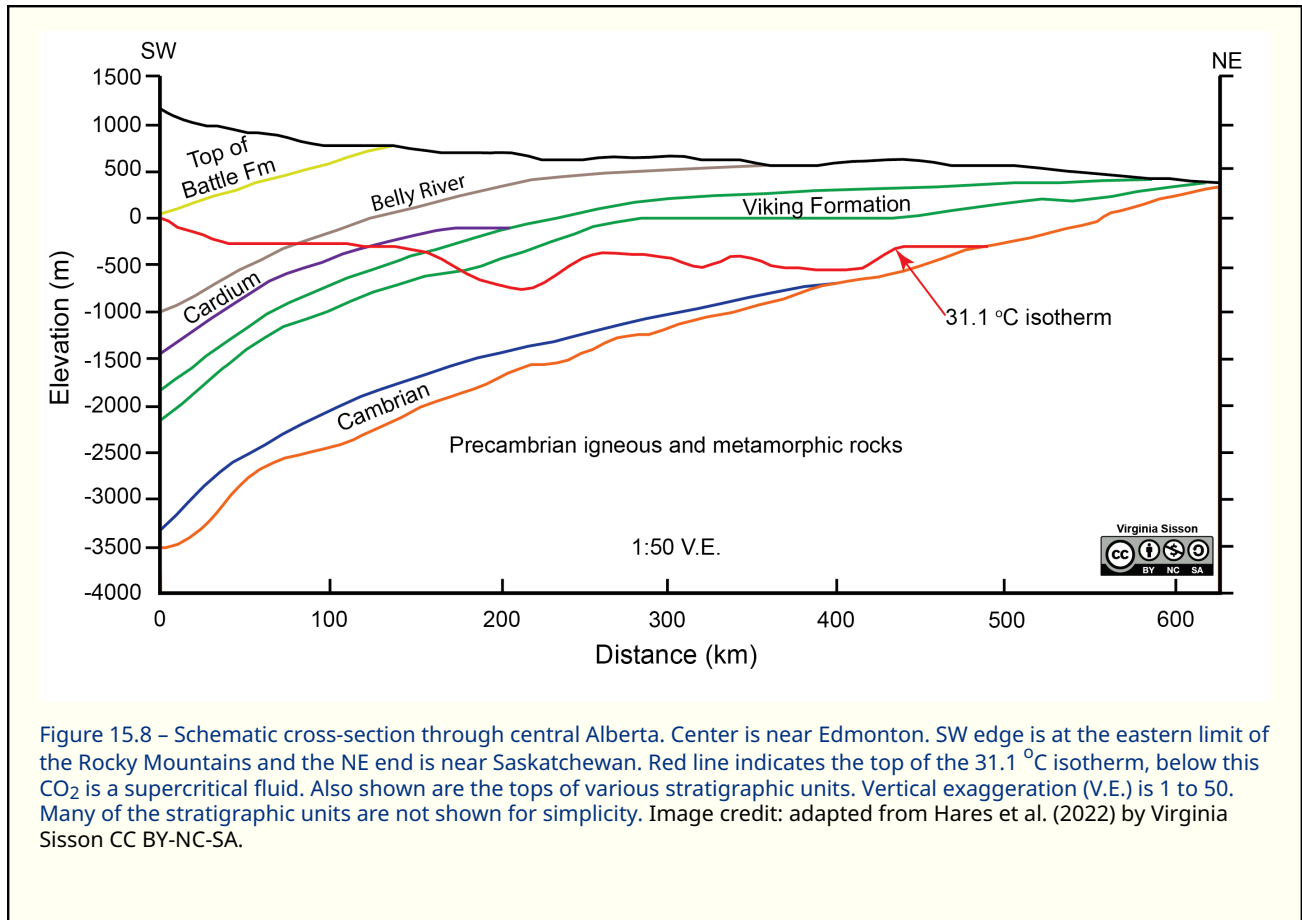


Figure 15.7 – Stratigraphic column showing geologic formations, approximate depths in m, and whether these formations are aquifers (sandstones in yellowish dotted pattern) or aquitards (shales and limestones in brown with dashed pattern). Image credit: adapted from Hares et al (2022) by V.B. Sisson CC BY-NC-SA.



Additional Information

Exercise Contributions

Michael Comas, Virginia Sisson, and Daniel Hauptvogel

References

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Intergovernmental Panel on Climate Change (IPCC). The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. In: *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press; 2023:923-1054. doi: [10.1017/9781009157896.009](https://doi.org/10.1017/9781009157896.009).

CHAPTER 16: GEOPHYSICS

Seismic Waves and Interpretation

Learning Objectives

The goals of this chapter are to:

- Evaluate seismic velocities of common Earth materials
- Understand how to set up and interpret a seismic survey
- Interpret a multibeam bathymetry survey

16.1 Seismic Wave Velocity

Seismology is a branch of geophysics that studies earthquakes and how seismic waves move through the earth. You have already studied earthquakes, so now you need understand how waves move in the Earth. Wave movement is the basis for seismic surveys, which can tell us a great deal about the earth's subsurface structures. We can learn about the large layers in the earth, such as the mantle and core, or much more locally, like the layers of rock at a building site.

You already know about P- and S-waves from studying earthquakes. The rate these moves (velocity) depends on rock type as well as the temperature, pressure, and orientation of the fabric. Figure 16.1 summarizes the velocity of many common rock types measured at the Earth's surface.

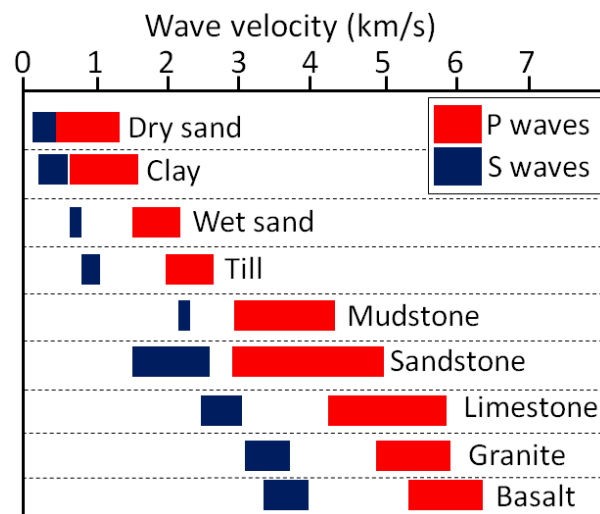


Figure 16.1 – Typical velocities of P-waves (red) and S-waves (blue) in sediments and crustal rocks. Image credit: [Steve Earle](#) CC BY-NC-SA.

Exercise 16.1 – Investigate Seismic Velocities

Your instructor is going to demonstrate how to use the V-Meter MK IV. This instrument sends an ultrasonic signal through materials to measure their properties. An ultrasonic signal is a sound that outside our hearing range. In this exercise, you'll be measuring the P-wave velocities of some common rocks such as gneiss, granite, marble, basalt, gabbro, and sandstone. Chose 3 of these from the samples provided.

- a. Using a caliper, measure the length of all sides of your samples (x, y, z). Repeat the measurements at least three times and calculate the average distance for each side in mm. Fill in your average length on Table 16.1.

Table 16.1 – Length of materials

Material	Length x (mm)	Length y (mm)	Length z (mm)
1:			
2:			
3:			

- b. Determine the density of your sample; density = mass/volume. You can determine the mass by using a scale and the volume by multiplying the three sides you measured in Table 16.1. For this exercise, volume needs to be in cubic centimeters (cm^3), so you'll need to convert your mm^3 to cm^3 by dividing it by 1000.

Table 16.2 – Density of materials

Material	Mass (g)	Volume (cm^3)	Density (g/cm^3)
1:			
2:			
3:			

- c. Measure the P-Wave velocity through each side of your samples. Record this information on Table 16.3. Calculate the average.

Table 16.3 – P-Wave velocity of materials

Material	V_x (m/s)	V_y (m/s)	V_z (m/s)	Average (m/s)
1:				
2:				
3:				

- d. Do your velocities match those in Figure 16.1? If not, why might there be a difference?

- e. Plot your density and P-wave velocity (the x, y, z, and average) data on the graph in Figure 16.2. Use different colors and symbols.

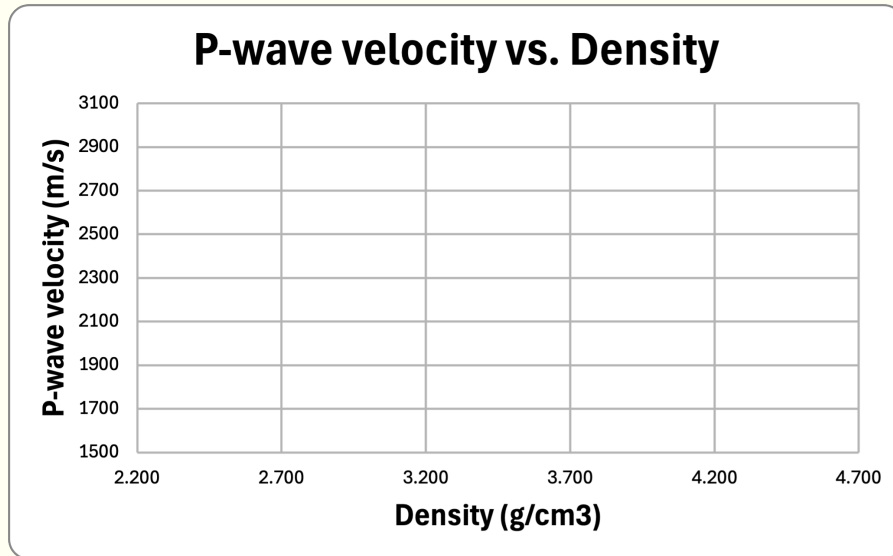


Figure 16.2 – Graph for plotting density and P-wave measurements.

- f. Discuss the relationship between the density of a material and how fast P-Waves move through it.

- g. **Critical Thinking:** If you measured P-waves in gneiss, are your P-wave results the same for all directions? Why do P-waves travel faster or slower through different sides of your materials?

- h. **Critical Thinking:** Depending on which sample you used, compare P-waves through gabbro versus basalt or granite versus gneiss. Are your results similar or different? Why?

16.2 Seismic Surveys

Seismic surveys are used to determine what lies beneath our feet or under the seafloor. They are commonly used in oil and gas exploration, but can also be used to find groundwater sources, investigate locations for potential landfills, determine how an area will shake during an earthquake, and more. These are like CT (computed tomography) scans of the subsurface. Seismic surveys use energy from controlled sources, typically a device that generates vibrations or sound waves. When these energy waves are sent into the Earth, they either reflect or refract through the layers sediment and rock because of differences in density (Figure 16.3). As these waves reflect or refract back to the surface, the energy is recorded by instruments called geophones. The data is then processed and visualized for geologists to interpret (Figure 16.4).

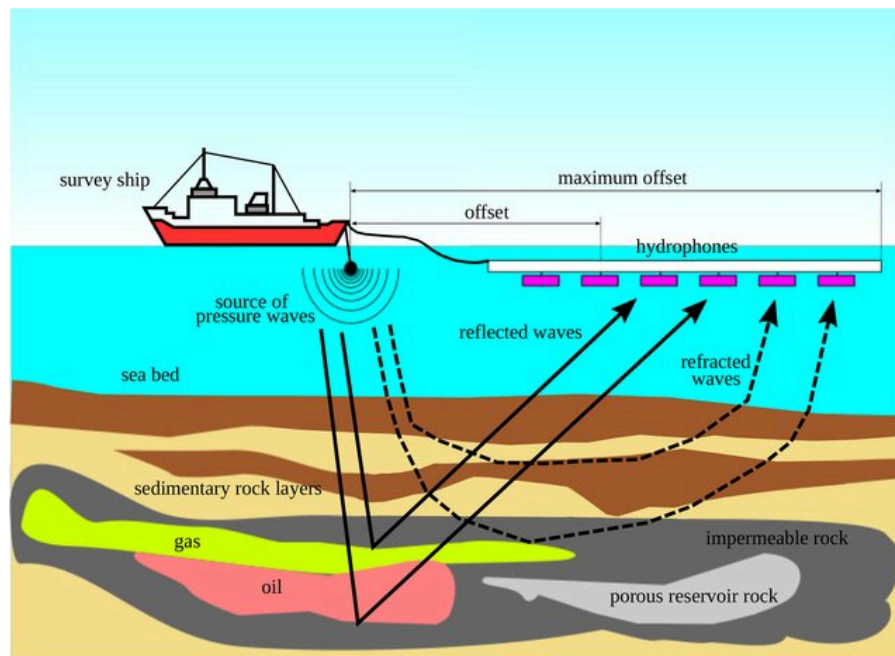


Figure 16.3 – A simplified illustration of a marine seismic survey showing reflected energy from various layers as well as refracted energy. This energy is recorded on geophones carried behind the ship. The offset is the distance from the ship to the geophone, with the maximum offset for the geophone at the end of the array. This arrangement with only one line of geophones will be processed and create a 2D seismic section. Image credit: Roberts et al. (2022) CC BY.

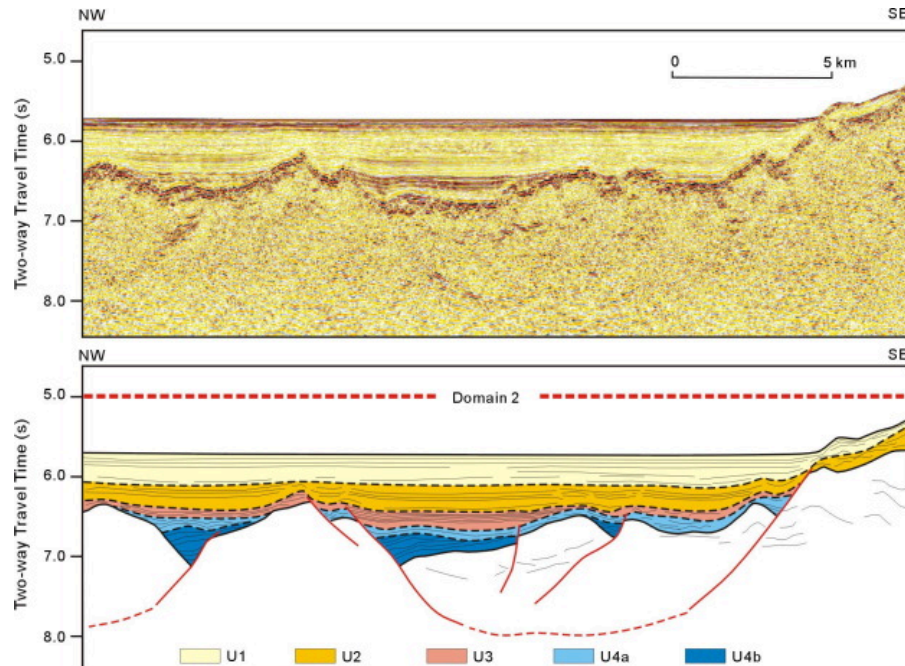


Figure 16.4 – Seismic section from the South China Sea. The upper image is the seismic data, and the lower image is an interpretation of the geology. The two-way travel time is measured in seconds (s) it takes for the seismic energy to be recorded at a geophone. Image credit: Ding et al., 2016, CC BY-NC-ND.

Exercise 16.2 – Conducting a Seismic Survey

Your instructor will set up a seismic survey at the front of the classroom. Use the hammer and record the signal on the seismometer. Notice how the signal changes from the first to the last geophone.

- After the seismometer records the direct wave (called a signal), is this record smooth or noisy? If it is noisy, what is the source of the noise?

- What happens if you change the distance between geophones?

- How can improve the quality (signal to noise ratio) of your shot record?

- d. Your results only record shallow structure? How would you set up this instrument to determine the deep structure similar to Figure 16.4 or Figure 16.5?

- e. **Critical Thinking:** Compare your shot record to those from earthquake seismograms (e.g. Figures 9.4 to 9.6). Why causes these differences?

3-D Seismic Surveys

Seismic surveys can be done in lines or arrays. Arrays are composed of lines at right angles. Why? Well, the result is a 3D image of the Earth (see Figure 16.5). The horizontal layers will show a map view through the area. These may not look like geologic map as these are maps of seismic amplitude. In addition, in the 3D volume, there will cross-sections. In marine 3D seismic surveys, the shooting direction (boat track) is called the inline direction. The perpendicular direction is called the crossline. In marine 3D seismic surveys, commonly, record more than 100,000 traces per square km.

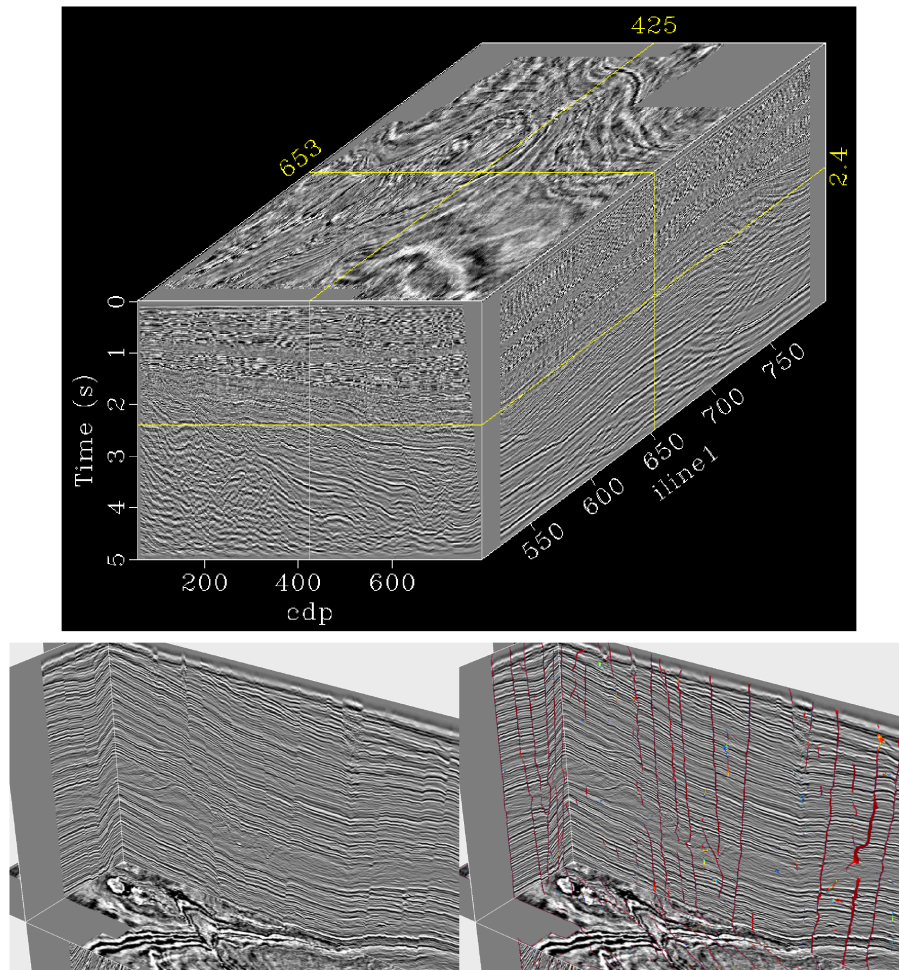


Figure 16.5 – 3D seismic survey done offshore of the South Island of New Zealand. A. full image showing time (equivalent to depth) on vertical axis with crossline (cdp) and inline (iline) images. B. An uninterpreted slice along an unknown inline section with some of the map data. C. Interpreted slice showing numerous vertical faults shown as red lines. Image credit: Seismic data from [New Zealand Petroleum and Minerals](#) posted on [SEGwiki](#) with interpretation by Xinming Wu CC BY-SA.

Exercise 16.3 – Interpret a Seismic Survey

The geologic history of the North Sea, between Norway and Great Britain, involves several tectonic events as well as significant sedimentation. In 1976, significant quantities of oil and gas were discovered with center of the North Sea now having many oil and gas wells. Since it is underwater, the only way to figure out what happened is to look at seismic surveys and/or drill holes. As of 2023, there were over 800 wells drilled just in the [Norwegian section](#) of this marine basin. Some of these were just for exploration and others have yielded significant quantities of oil and gas.

First look at the stratigraphic column that shows the rock units for this region (Figure 16.6). Each blue, white and red line represents different rock layers with different seismic velocities or amplitudes. using a color scheme with blue for positive amplitudes, red for negative amplitudes, and white for zero amplitude. Notice

whether these layers are continuous, discontinuous as well as how bright is the color. These combinations of these features are called seismic attributes or characteristics.

- a. Describe characteristics of the Neogene units compared to the Paleogene units.

- b. Describe how you would identify the base of the Cenozoic

- c. How many distinctive layers are there in the section from Cretaceous to Jurassic? How can you identify the base (bottom) of this sequence?

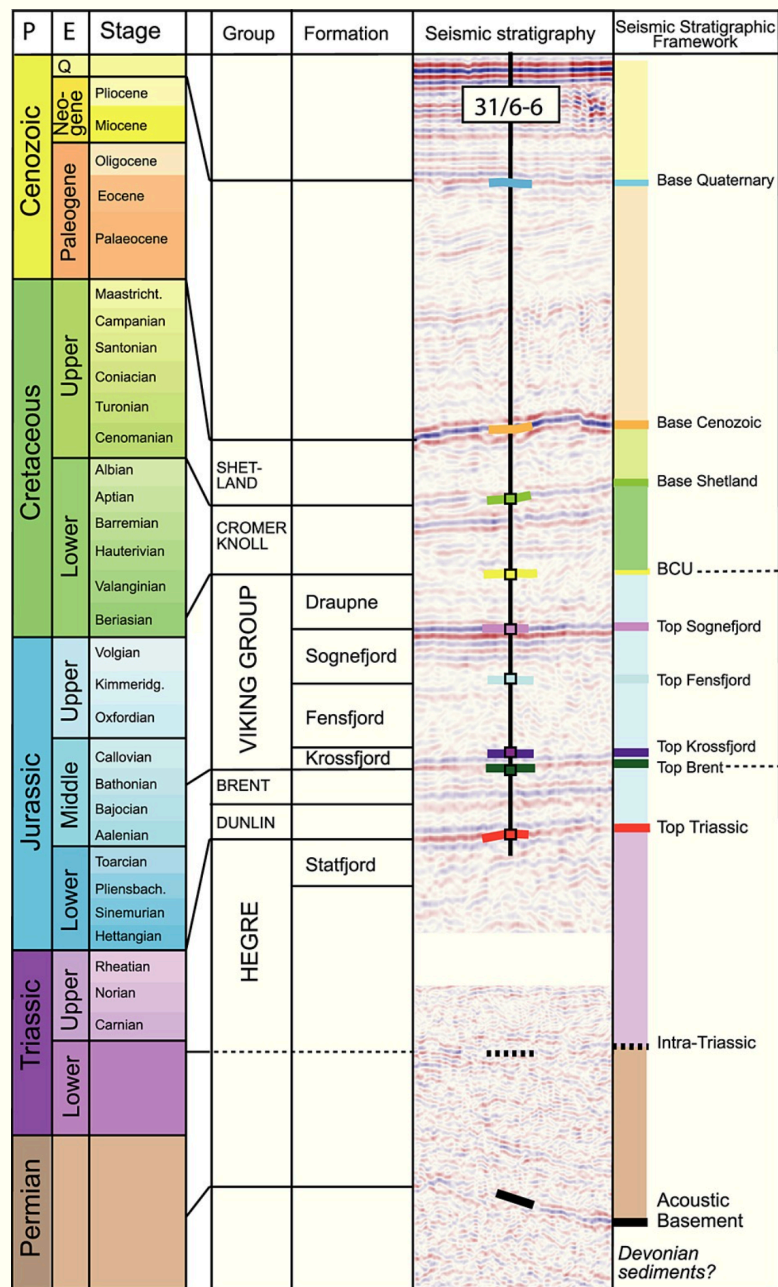


Figure 16.6 – Stratigraphic column with data from well 31/6-6. This well data was used to construct a seismic stratigraphic section for the different rock types. Geologic time is subdivided into P = Period, E = Epoch. In the right-hand column are the boundaries between different units as identified by seismic data. The blue color is used for positive amplitudes, red for negative amplitudes, and white for zero amplitude. Image credit: Bell, Jackson, Whipp and Clements (2014) CC BY.

- Now that you can identify the different types of rocks, mark the boundaries between these units on Figure 16.7. If the layers are not continuous, there may be faults or folds.
- Identify and mark at least 3 faults on this figure. What type of faults? What is the tectonic environment?

f. Are there any unconformities in this seismic section? If so, what type?

g. Critical Thinking: Why are there so many drill holes in this area?

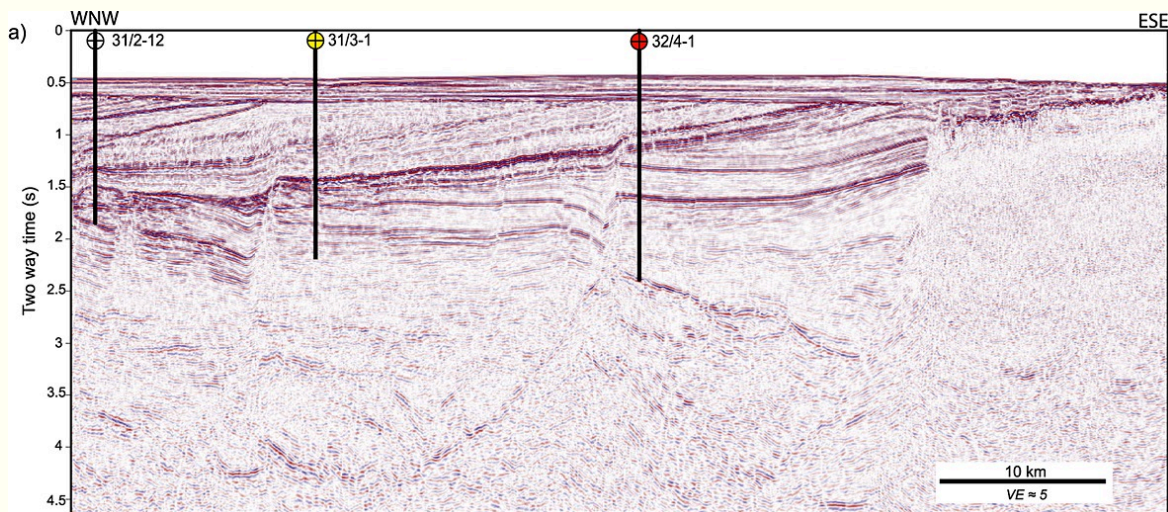


Figure 16.7 Uninterpreted 2D seismic reflection profile across the Horda Platform in the North Sea between Norway and Great Britain. The vertical axis represents the time it took for the seismic energy to be recorded at the geophone array. The white area at the top is the ocean. The colored lines represent different seismic amplitudes with blue for positive amplitudes, red for negative amplitudes, and white for zero amplitude. The vertical lines are locations of drill holes. VE = vertical exaggeration. Since this is vertically exaggerated, dipping lines will appear steeper than they actually are. Image credit: [Bell, Jackson, Whipp, and Clements \(2014\)](#)

16.3 Sonar

So far, you've only had exercises about seismic waves but there are many other physical properties that can be used to study Earth such as gravity, magnetism, and electricity. These all can be used to study what is below the Earth's surface. Instead, let's do one final exercise to study the surface of the Earth. You've seen many topography maps in this lab manual. Ever wonder how these are made? Now, most surface elevation data is obtained using data from satellites, or satellite altimetry. These use either radar or sonar signals to measure heights (altimetry). Another technique is to use sonar instruments that are towed behind ships to map the seas floor. For the oceans, much of this data is in a national repository, Global Multi-Resolution Topography (GMRT). As of May 2024, this web site had data for 40,838,234 square kilometers of multibeam sonar data from 1,490 cruises! This may seem like a lot of data, but it is only about 8% of the area of all oceans. So, there is a lot we don't know about the ocean floor.

Exercise 16.4 – Interpret Multibeam Sonar Surveys

Ocean basins have lava flows erupted a mid-ocean ridges and volcanos scattered throughout them. There are so many volcanos that most are unnamed. The world's tallest volcano is Mauna Kea measured from the ocean floor to its peak on the Big Island of Hawaii. These volcanos can be used to learn about the history of ocean basins as well as magmatism in these areas.

First look at Figure 16.8.

- a. Describe the characteristics of this volcano including its height above the sea floor and its approximate volume using the formula for a cone ($\frac{1}{3} \pi r^2 h$) with r for radius and h for height.

- b. Using this information can you determine if this is an old or young volcano?

- c. Go look back and look at Figure 6.8 and your results from Exercise 6.5. Do you think this volcano is the result of one or many eruptions? How did you determine this?

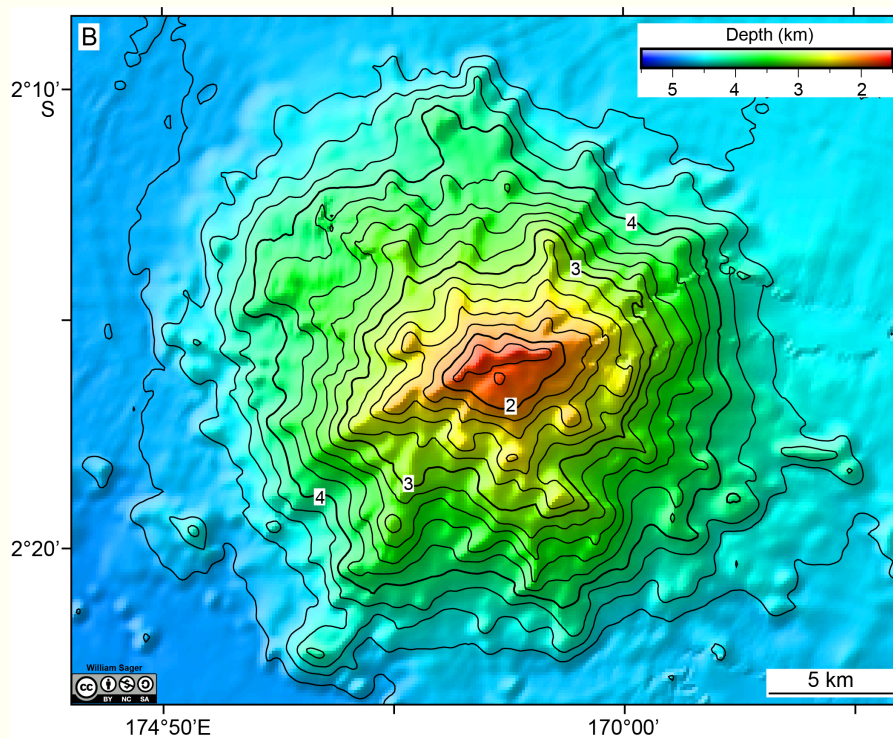


Figure 16.8 – Schematic color-coded bathymetric map of an unnamed volcano in the Pacific Ocean. Note that the colors correspond to depth beneath the ocean surface with cooler colors for deeper depths and warmer colors for shallower depths. Contour intervals are 200 m, with thicker lines at 1 km intervals. Image credit: William Sager, CC BY NC SA.

The Louisville Ridge is an underwater chain of over 75 seamounts located in the southwest Pacific Ocean. It stretches for 4,300 km (2,700 mi) making it the longest seamount chain on Earth. Remember exercise 3.6 about the Hawaiian hotspot. Well, this volcanic chain results from movement of the Pacific Plate over the Louisville hotspot. The volcanos range from 77 Ma at the NW end of the chain to 1.1 Ma at its SE end; this is age spread is similar to the Hawaiian Emperor seamount chain. In lecture, you may have learned about how some oceanic volcanic islands erode and form guyots (flat topped volcanoes) and then coral atolls. So, the shape of the volcano may help you determine its age. To do this you need to determine if the volcano was ever high enough to be above the sea floor. Examine the two volcanoes in Figure 16.9.

- d. Describe the characteristics of these two volcanoes including their height above the sea floor and their approximate volume using the formula for a truncated cone ($\frac{1}{3} \pi [(r^2 + r) \times (R^2 + R)]h$) with h for height, r for radius of the top of the flattened area and R is the radius for the bottom of the volcano.

- e. These two volcanoes have features that look like spokes of a bicycle wheel. How did these form?

- f. Do you think these flat-topped volcanoes (guyots) were formed by eruption or by erosion. Why?

- g. **Critical Thinking:** How much magma was erupted in the two areas? Compare the volcanoes in the Figures 16.8 with 16.9, especially their volume. Do you think the oceanic lithosphere has different thickness in the two areas?

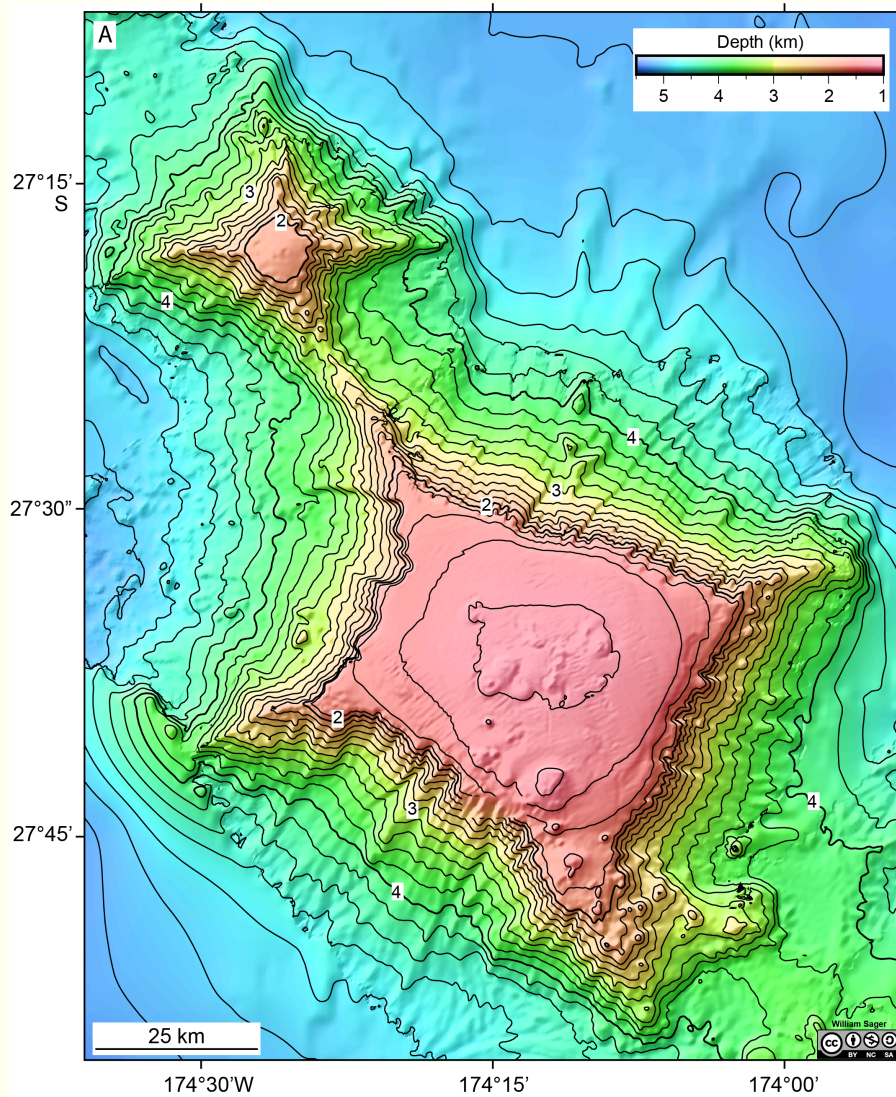


Figure 16.9 – Bathymetry of two volcanoes of the Louisville seamount trail. These are close to the northwest end of the seamount trail. Thus, they are some of the oldest seamounts. This image was produced for IODP Expedition 330. Note that the colors correspond to depth beneath the ocean surface with cooler colors for deeper depths and warmer colors for shallower depths. Contour intervals are 200 m, with thicker lines at 1 km intervals. Image credit: William Sager, CC BY NC SA.

Additional Information

Exercise Contributions

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