2022

Geology Online Lab Activities An Open Educational Resource for Community College Students and Instructors

Rondi Davies
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By Dr. Rondi Davies

Queensborough Community College CUNY

Image of Manhattan schist, Central Park, New York by [G. Scott Segler], [CC-BY-SA-4.0]

Table of Contents

Introduction
The online geology lab for community college students was developed by Dr. Rondi Davies, a faculty member at Queensborough Community College, City University New York, during two years of forced online synchronous learning brought on by the COVID-19 pandemic. This open educational resource collects many of Dr. Davies' favorite open-access materials and supplements them with her own work within a single, cohesive laboratory manual intended for two-year, non-major college students from the New York area.

Dr. Davies wanted to develop labs that were fun, engaging, and that excited students about the subject, were relevant to their lives, helped them to grow as scientists, and even opened their minds to the possibility of a career in STEM and the geosciences. Strategies adopted to achieve these goals include collecting and interpreting data to simulate the scientific process and develop student confidence and self-efficacy, sketching, role-playing as a scientist, and reasoning by analogy to help students feel appreciated and valued.

To enhance relevance and meaning-making, the labs are grounded in the geologic history of New York. Each lab is structured to meet students at their level of knowledge and build on what they know. They follow a 5E instructional approach (Engage, Explore, Explain, Elaborate, Evaluate; Bybee et al., 2006), which is based in educational theory about how students learn and fosters conceptual change. The labs also use anchoring phenomena and modeling to engage students and show their learning.

Each of the twelve labs was designed to be covered in a three-hour class within a 15-week semester. The introductory lab is about observation and interpretation and how the process of science is much like solving a mystery. Mineral resources, plate tectonics, and igneous, sedimentary, and metamorphic rocks provide much of the foundational material. This is followed by more exploratory labs on earthquakes, the glacial and geological history of New York, and climate change. The final lab, an in-person or online field trip guide to the Hall of Planet Earth at the American Museum of Natural History, draws on all the topics covered in previous labs.

Each lab is accompanied by a Teacher's Guide and an online answer sheet (formatted for the Blackboard learning management system). A multiple-choice format is used for many questions, making the labs easy to grade.

The materials were developed, tested, and refined over two years of synchronous remote learning between 2019 and 2021. Although developed for online learning, they can easily be utilized for in-person classes.

I hope you find these labs enjoyable and beneficial to use. Please in touch if you have any edits, questions, or comments (rdavies@qcc.cuny.edu).

About the Author
Dr. Rondi Davies is an Assistant Professor in Geology at Queensborough Community College, City University of New York. She is also a Research Associate and former faculty of the MAT program at the American Museum of Natural History. Rondi received her PhD in Geology at Macquarie University in Sydney Australia. She has worked as an Earth science educator in many different settings and has researched and developed science content for educational software groups, text books, and museums.

References
Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. (2006). The BSCS 5E instructional model: Origins, effectiveness, Colorado Springs, Co: BSCS, 5, 88-98.

1. How do scientists study Earth?

Observing and interpreting phenomena are the foundation of the endeavor of science.

Purpose

The main goal of this lab is to become familiar with the idea that geology is something tangible and that it affects the world around you. You should be inspired to ask questions about how geologic processes shaped the world and make observations to answer those questions. You will explore the concepts that geology is a historical science; that scientific endeavor, like geology, is based on incomplete evidence; and that scientific endeavor is uncertain because it is a human activity and thus filled with biases.

Learning objectives

After doing this lab you will be able to:

1. Discuss how geology is a lot like detective work.
2. Explain the difference between observation and interpretation.
3. Explain how an interpretation in geology (and crime) requires ordering a sequence of events.
4. Explain how science explanations are less certain when they are based on indirect information.
5. Discuss how in science there is not an exact answer, rather a best answer.

Introduction: observation versus interpretation

An **observation** is any report from your five senses. It does not involve an explanation. An **interpretation** is an attempt to figure out what has been observed. Interpretations are stories about what happened based on observations.

The endeavor of science: Science is built on evidence, or clues, that can be observed or deduced from the natural world. We gather evidence through the use of our senses. However, evidence can be confusing, sometimes conflicting, and seemingly random. Data is not always consistent or even readable. Furthermore, all of the evidence may not be available. This is why scientific explanations are tentative explanations of natural phenomena. There are degrees of tentativeness. These range from very tentative (or very uncertain, with very few clues) to very durable (with lots of supporting evidence from many studies).

What's the difference between a hypothesis and a theory? A **hypothesis** is a very tentative explanation, relatively untested, for something puzzling. They must account for all the known evidence or data, be logical, and be testable. To test a hypothesis you should look for certain clues to see if they fit the current hypothesis, or not. Hypotheses are rarely correct. A **theory** is a much better-established explanation, based on tested hypotheses and more observations. A theory is still tentative and subject to change, but it is more robust than a hypothesis.

Part I. Murder or suicide? – ENGAGE & EXPLORE

To understand the difference between observing what you see and interpreting it through your personal lens, observe Figure 1 and answer the following questions.

Figure 1. From Is this murder or suicide picture puzzle, Puzzles.

Question 1. Was this a murder or suicide? List the reasons why you have come to this conclusion?

Figure 2. From Meeks, R. Peeping toms, Wikimedia Commons

Question 2. In Table 1, write both what you observe in Figure 2 and what you infer is going on.
Table 1.

No	Observation. What do you see?	Interpretation. What is going on? Why?
Example	The man on the right is wearing a leather jacket.	The man rides a motorbike and is in a gang.
1		
2		
3		

Question 3. Based on your observations and interpretation of Figure 2, what do you propose is going on in the picture?

Question 4. Did you learn anything about your own personal preconceived opinions or biases by answering questions 2 and 3? Explain.

Part II. Observation and interpretation of geological features – EXPLAIN

Question 1. Observe the four images in Figure 3. Use Table 3 to report on your observations and interpretations of how these features formed. Your instructor will review your findings before continuing.

Figure 3. Image 1. By Editor5807, CC BY 3.0 **Image 2.** By author R. Davies


Image 3. By NASA.gov

Image 4 . by Wally Gobetz, CC BY-NC-ND 2.0

Table 3.

No.	Observation. What do you see?	Interpretation. How did this form?
1		
2		
3		
4		

Part III. Venmo activity – ELABORATE

Simulating the endeavor of science. In this simulation, there are several independent types of observations, or clues, that may be used to develop an interpretation (hypothesis). This illustrates the concept that scientists use a variety of criteria to compare explanations and select the better ones (the ones that fit all the data). Scientists are always looking for patterns in their data. They may connect seemingly unrelated lines of evidence to form tentative explanations.

Scientific bias. Evidence in science, as in this simulation, is not of equal value. Scientists must learn to tell the difference between useful and useless data. In this activity, the value of each Venmo statement is affected by the order in which it is selected, and by the relative importance placed upon it by the various group members. Individuals with strongly held opinions, biases, beliefs, or with strong personalities may have a major influence on their group's opinions. This aspect of the activity illustrates that human values, biases, and experiences can deeply influence science.

Adapted from The Checks Lab. (n.d.). Adapted by Steve Randak; version by Judy Loundagin, ENSI website.

There is only a best answer in science. This lab is open-ended. There is not enough information to say with certainty what the storyline is, and each new Venmo statement may create more questions than answers. You should recognize that not everyone reaches the same conclusion when observing the same data, and why that is.

Science is a collaboration. This activity demonstrates the value of collaboration within each group and with other groups in order to arrive at a reasonable explanation of the problem. Scientists often work together to solve problems. Keep in mind that collaboration often involves scientific argumentation, where every claim requires evidence that supports it. Members of the scientific team must insist on that evidence for every claim. This is how they eventually arrive at the best explanations. Collaboration also reduces the effects of personal biases.

Investigation versus experiment. Finally, notice that this investigation is not an experiment. Science can be done on events of the past, unobserved by anybody, and unrepeatable. Therefore, you must search for clues to explain a series of past events, looking for patterns and connections. This type of science is usually referred to as historical science.

The process of science. The main point of this activity is to experience never having all the information (clues) that you might want. Because of lacking information, you have to settle for the most likely explanation that fits all the evidence that you do have. You hope that you are at least close enough to the real explanation to make that information useful. This is a simulation of how science really works. If you wanted to know what the real story was, then you experienced the frustration that scientists have, which makes them keep trying to find more clues. Also, clues usually trickle in over long periods of time, and the "story" (explanation) may change over time with new clues. The bank statements you do not see were like those clues that a scientist may never see.

Step 1. Students, arrange yourselves into groups of four and look at Venmo statement 1. These statements were found in different drawers in the home of a family that no longer lives there.

Step 2. Look at Venmo 1 page at the back of the lab. Using the information on the statements, determine the circumstances that surrounded the writing of the bank statements and come up with a storyline for the characters based on the information on the statements. Formulate a tentative explanation #1 for the statements or a "storyline" that fits the statements. Write down your explanation.

Question 1. Tentative explanation #1

Step 3. View Venmo 2 and view four more payment statements. After a period of time, some more statements are found in another drawer of the evacuated house. How does this new information affect the previous storyline? Formulate a tentative explanation #2 for the statements or a "storyline" that fits the statements. Write down your explanation.

Question 2. Tentative explanation #2

Step 4. View Venmo 3 and proceed as before, and record tentative explanation #3.

Question 3. Tentative explanation #3

Step 5. Select your group's strongest explanation (likeliest storyline) and record this as your final tentative explanation.

Question 4. Final tentative explanation

Step 6. Select a group spokesperson to report the group-selected explanation (storyline) to the class, so that all may hear different conclusions from similar data.

Part IV. How are geology and detective work alike? – EVALUATE

Question 5. Even if scientists have a strong explanation of a natural phenomenon, they can never be absolutely sure that new data won't eventually appear and show the explanation to be wrong. What bits of information on the Venmo statements were most useful to your group in formulating a tentative explanation?

Question 6. What information was not useful to your group in formulating a tentative explanation?

Question 7. List any misleading information that was presented.

Question 8. Why do we say that an explanation in science is "tentative" (this is also known as a hypothesis)?

Question 9. How could you test your hypothesis?

Question 10. Did you experience any bias when making your tentative explanation? Explain.

Question 11. Besides geology, what are some other examples of historical science that does not conduct experiments as much as look for clues from the past to support a hypothesis and develop a theory?

Sources

Getting started: Sample starting activities. *The Checks Lab*. (n.d.) Understanding Science. University of California Museum of Paleontology. 3 January 2021 from https://undsci.berkeley.edu/teaching/912_activities.php

The Checks Lab. (n.d.). Adapted by Steve Randak; version by Judy Loundagin, ENSI website. 3 January 2021 from https://evolution.berkeley.edu/evolibrary/teach/ensi/ensi_checks_lab.html

Image Sources

Figure 1. *Is this murder or suicide picture puzzle*. Puzzles. (1970, January 1). Retrieved January 6, 2022, from https://www.puzzles-world.com/2017/11/is-this-murder-or-suicide-picture-puzzle.html

Figure 2. Meeks, R. (2005, December 31). File:*peeping toms* (106437231).JPG. Wikimedia Commons. Retrieved January 31, 2022, from https://commons.wikimedia.org/w/index.php?curid=35916619

Figure 3. Image 1. *Newport Whitepit Lane pot hole.JPG* by Editor5807 is licensed under CC BY 3.0

Figure 3. Image 2. Credit author (R. Davies)

Figure 3. Image 3. NASA.gov

Figure 3. Image 4. Wally Gobetz, *NJ - Pyramid Mountain Natural Historic Area: Minnen Trail - Tripod Rock* by Wally Gobetz is licensed under CC BY-NC-ND 2.0.

venmo

From: Gabriela Garcia
200 31st Road, Bayside, NY 11360

To: FAO Schwarz

Date: June 25, 2005

For: Lego

Amount: $70.23

venmo

From: Ang Nakumura
200 31st Road, Bayside, NY 11360

To: Lenox Hill Hospital

Date: October 2, 2001

For: Dr. Kremer Ob/Gyn

Amount: $3300.00

venmo

From: Ang Nakumura
200 31st Road, Bayside, NY 11360

To: Modell's Sporting Goods

Date: June 25, 2011

For: Nike Air Max, size 8

Amount: $99.59

venmo

From: Gabriela Garcia
200 31st Road, Bayside, NY 11360

To: Nikki Chang

Date: May 20, 2003

For: Babysitting

Amount: $150.00

venmo

From: Gabriela Garcia
200 31st Road, Bayside, NY 11360

To: Crisis Marriage Counseling

Date: April 5, 2016

For: Dr. Benhaim

Amount: $300.00

venmo

From: Gabriela Garcia
200 31st Road, Bayside, NY 11360

To: Camp Hillard Day Camp

Date: July 5, 2013

For: Summer Camp - Marco

Amount: $5000.00

venmo

From: Ang Nakumura
200 31st Road, Bayside, NY 11360

To: Circuit City

Date: August 26, 2017

For: Apple Air

Amount: $959.00

venmo

From: Ang Nakumura
15 Maiden Lane, Apt 27, New York, NY 10038

To: Memorial Sloan Kettering Cancer Center

Date: January 16, 2018

For:

Amount: $2200.00

venmo
From: Marco Nakumura
200 31st Road, Bayside, NY 11360

To: Never Forget 9-11 Foundation
Date: September 11, 2021

For: Donation
Amount: $200.00

venmo
From: Gabriela Garcia
200 31st Road, Bayside, NY 11360

To: Forest Hills Mortuary
Date: December 2, 2020

For: Cremation Services
Amount: $8900.00

venmo
From: Ang Nakumura
15 Maiden Lane, Apt 27, New York, NY 10038

To: Gingiss Formal Wear
Date: June 3, 2018

For: Tuxedo rental
Amount: $150.00

venmo
From: Ang Nakumura
15 Maiden Lane, Apt 27, New York, NY 10038

To: Tiffany Jewellers
Date: February 14, 2016

For: Gift
Amount: 650.00

2. Mineral resources and how we use them

What's inside my cellphone?

Introduction

Minerals are the building blocks of rocks and the Earth. To understand rocks we need to become familiar with minerals and their properties. Minerals are also important because they are used in almost everything around us including electronics, ceramics, construction materials, and jewelry.

Purpose

The purpose of this lab is to explore what a mineral is, how the properties and abundance of these natural resources are harnessed for uses in our everyday lives, and how they are a finite resource having formed in the Earth over long periods of time.

Learning Objectives

After doing this lab you will be able to:

1. Define minerals and mineral resources.
2. Give examples of mineral resources and products that contain them.
3. Summarize the properties that make minerals useful.
4. Explain why minerals are a finite resource.

Part I. Earth materials in your life – ENGAGE

Question 1. Look at your possessions and the room around you. Can you identify any objects or parts of objects that are made from mineral resources? List three objects and the minerals you think they are made of.

Object	Mineral Resource
Example: Window glass	Quartz or silicon dioxide
1.	
2.	
3.	

Question 2. Are there any objects around you that are not made of minerals?

Definition of a mineral

Minerals are any substances that have all of the following characteristics:

1. **Solid**. Not liquid, not gas, not plasma.
2. **Inorganic or not made from living materials**. Some minerals, like our teeth or shells, were created by organic processes. However, because they are not made of organic matter, we still consider them to be a mineral.
3. **Naturally occurring or made in nature.** Some minerals are made in labs such as synthetic diamonds. Since synthetic diamond is chemically and structurally the same as a natural diamond, it is considered a mineral. However, cubic zirconia, which is made only by people and not by nature, is not a mineral.
4. **Chemically homogeneous**. This means that the mineral contains the same chemical elements throughout the mineral. Therefore, you can write one chemical formula that describes the entire mineral (Table 1).

Table 1.

Mineral	Chemical formula	Elements in these minerals
Quartz	SiO_2	Si = silicon, O = oxygen (there are two oxygen atoms for every one silicon atom)
Hematite	Fe_2O_3	Fe = iron, O = oxygen (there are two iron atoms for every three oxygen atoms)
Diamond	C	C = carbon
Halite	NaCl	Na = sodium, Cl = chlorine

5. **Crystalline.** This means that the atoms in a mineral are arranged in an orderly and repeating three-dimensional pattern (Fig. 1).

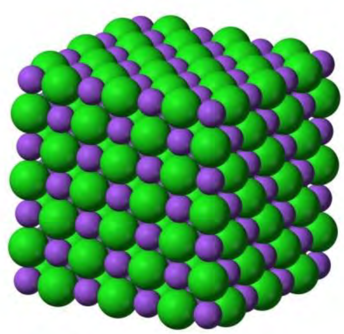


Figure 1. Sodium (Na - purple) and chlorine (Cl - green) atoms form cubes, and these cubes repeat themselves to make the mineral halite. From Goran tek-en, CC BY-SA 4.0.

Note: The "minerals" in cereal or a bottle of vitamins are not real minerals. They are elements that may have been extracted from minerals.

Mineral Resources

Mineral resources are any mineral or rock mined from the Earth and used by humans for some purpose. Examples include gold, silver, lead, iron, and diamond. Brines (salty waters) and sands are also “mined” for the minerals they contain.

Minerals resources developed over the more than four-billion-year history of the Earth and are **nonrenewable**. This means they cannot be readily replaced by natural means at a quick enough pace to keep up with consumption.

Common elements and common minerals

Minerals are composed of elements. Eight elements make up the majority of minerals in Earth's crust and mantle. In decreasing order of abundance these elements are oxygen (O), silicon (Si), potassium (K), calcium (Ca), sodium (Na), aluminum (Al), iron (Fe), and magnesium (Mg) (Fig. 2). These elements can combine in a variety of ways to make different minerals. Most minerals contain silicon and oxygen (plus other elements). These minerals are called silicate minerals.

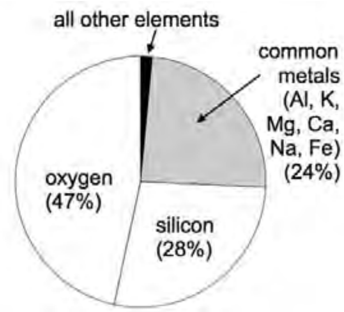


Figure 2. elements in Earth's crust (by mass).

Why are silicate minerals important?

Sustainability. The eight elements found in silicate minerals (listed above) are the most common and available for use. Other elements are more rare; we find them less frequently and have a lower overall supply of them.

Extracting ore from nonsilicate minerals. Although the majority of Earth's elements are found in silicate minerals, metallic elements (e.g., gold, silver, lead, zinc) are usually found in higher proportions in nonsilicate minerals such as oxide or sulfide minerals. If mining companies want to extract an element from a mineral, they seek nonsilicate minerals that contain the element. Even though those minerals are less common and harder to find, it is more efficient (fewer resources are needed) to extract elements from nonsilicate minerals. For example, the silicate mineral fayalite (Fe_2SiO_4) contains a higher percentage of iron than the oxide mineral hematite (Fe_2O_4), but hematite, not fayalite, is mined for iron because it is easier to extract iron from hematite.

Mineral properties

A mineral's chemical and crystalline nature gives it properties that make it useful. Some of these properties also must be considered when determining how to best mine and process the mineral ore and dispose of the mine waste.

1. **Chemistry.** The elements within minerals give those minerals distinct and useful properties. For example, sulfur allows gunpowder to ignite at a lower temperature and provides fuel for the fire. Sulfur can be found as a mineral, or as an element within other minerals like pyrite (Fig. 3). Aluminum is a very lightweight but strong metal. Aluminum does not form a mineral on its own but is extracted from the mineral gibbsite.

Figure 3. Sulfur (S) can be mined from native sulfur (left) or sulfide minerals such as pyrite (FeS, right). Images by J. Branlund

2. **Hardness.** A mineral's hardness is determined by the crystalline nature of that mineral, specifically, the type and strength of bonds that hold the atoms together, and the nature of the repeating pattern. Very hard minerals (like diamond, corundum, and garnet) are useful as abrasives. For example, saw blades impregnated with diamonds can cut rock, and sandpaper is often made with garnet sand. Muscovite is used in glitter and make-up because it is a very soft mineral (Fig. 4).

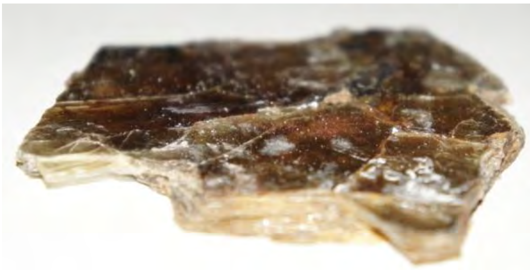


Figure 4. Muscovite is soft and sparkly and is used in glitter. Its one plane of cleavage causes it to break into sheets. Image by J. Branlund.

3. **Behavior of light in the crystal.** The crystalline structure determines how light interacts with a mineral. Light reflects inside of diamond, which gives a diamond ring an exquisite sparkle. Other minerals (like rutile) are quite opaque, which makes titanium oxide (the chemical name of rutile) an important additive in things that need to be opaque, such as paint and sunscreen.

4. **Luster** describes how light interacts with the surface of a mineral. The mineral hematite can have both metallic or nonmetallic luster; hematite with metallic luster is used to make jewelry. Some minerals are also useful in blocking other wavelengths of light; for example, lead (from the mineral galena) blocks X-rays.

5. **Color.** Some minerals have distinct and vibrant colors. This makes them incredibly useful as pigments in paints, cosmetics, colored plastic, etc. For example, the rust-red color of hematite and the bright green color of malachite are used as pigments in paints (Fig. 5).

Figure 5. The rust-red color of hematite and green color of malachite have long been used as pigments. Images by J. Branlund.

6. **Specific gravity.** Specific gravity is a relative density, determined both by a mineral's chemistry (minerals containing heavier elements will have higher specific gravities) and how closely together the atoms are packed.

7. **Crystal shape and cleavage** are determined by the nature of the crystalline structure. The sheet-like cleavage of muscovite (Fig. 4) allows it to be broken into tiny pieces of glitter.

8. **Solubility.** The property of the crystalline structure (the type of bonds) and chemistry causes different minerals to dissolve differently. Some dissolve quickly in water (e.g., salt or NaCl), whereas others are very stable. The pH or acidity of water also affects solubility; some minerals will dissolve faster in acidic water (e.g., calcite), whereas others might dissolve more readily in alkaline waters.

   For some applications, an insoluble mineral is preferred. For example, the Brooklyn Bridge that spans between Manhattan and Brooklyn is faced below the water line with rock made of insoluble minerals, whereas more decorative limestone (made of the more soluble mineral calcite) faces the support above the water line (Fig. 6). Other applications favor soluble minerals; in mining it is easier to extract a desired element from a soluble mineral.

Figure 6. Below the water line the Brooklyn Bridge is faced with rock made of insoluble minerals. Limestone, a more soluble mineral, faces the support above the water line. Image from Ankur Agrawal, CC BY-SA 3.0,

9. **Magnetism**. The chemistry of certain minerals allows them to store an applied magnetic field. For example, magnetic minerals such as magnetite in a hard drive can be programmed to store information.

10. **Electrical conductivity.** The electrical conductivity is mainly determined by the types of chemical bonds; metallic bonds cause metals to have high electrical conductivity, and these are favored for wires (Fig. 7). Minerals that have low electric conductivity will be used for insulators, to block or confine the electric current.

11. **Thermal conductivity.** Minerals can also be used to conduct heat or confine heat. Thermal conductivity is determined by both a mineral's chemistry and crystalline structure.

12. **Melting point.** Different minerals melt at different temperatures. Minerals with high melting points are used for high-temperature applications. For example, asbestos is used in fire-resistant fabrics because of its high melting point.

Figure 7. Copper's electrical conductivity and resistance to corrosion make it ideal for electric wiring. Although copper can be found as a pure metal (native copper, lower right), it is often extracted from minerals like chalcopyrite (CuFeS2, upper right).
Images by J. Branlund

13. **Behavior in response to stress.** Some minerals/rocks are brittle or break easily and some are ductile or can bend. For example, gold is malleable, which allowed early peoples to easily shape it into ornaments. An electric current is generated in piezoelectric minerals when a stress is applied. For example, when a hammer hits a piezoelectric crystal, this will generate a spark to ignite a cigarette lighter. The piezoelectricity of quartz allows it to be used to tell time (in quartz crystal watches), and piezoelectricity is also useful in transformers and motors.

14. **The use of minerals and rocks in products.** Minerals and rocks are used in everyday products that surround us. The rock granite is mined to make countertops, and the mineral halite is mined, crushed, and sold as table salt. Other times, minerals are processed to extract one specific element or ore. For example, the commodity aluminum is extracted from the rock bauxite, which contains aluminum-bearing minerals like gibbsite (Fig. 8).

&

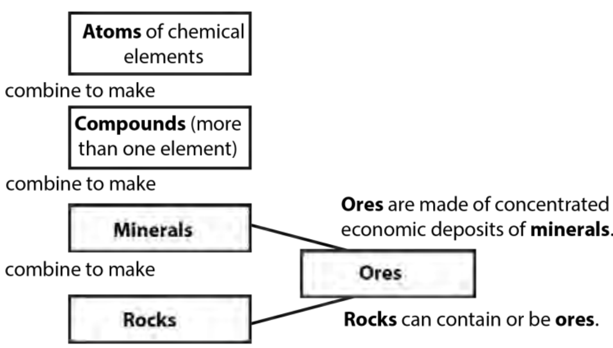


Figure 8. Concept diagram showing the relationships between atoms, elements, compounds, minerals, rocks, and ores or mineral resources. Modified from Bhattacharyya, P. Branlund, J. Activity 1.1. *Minerals and Products*, SERC Carleton InTeGrate

Part II. Earth materials and everyday life – EXPLORE

Question 1. Determine which mineral from Table 2 is in each product listed in Table 3. Use the minerals chemical formula and other properties of the minerals from the Mineral Worksheet handout to match them to the products listed in Table 3. (Choose 1 mineral per product.) Fill Table 3 with your answers.

Table 2

No.	Mineral Name	Chemical Formula
1	Bauxite	$Al(OH)_3$ - $AlO \cdot OH$
2	Calcite	$CaCO_3$
3	Chalcopyrite	$CuFeS_2$
4	Galena	PbS
5	Graphite	C
6	Gypsum	$CaSO_4 \cdot 2(H_2O)$
7	Halite	NaCl
8	Hematite (red)	Fe_2O_3
9	Kaolinite	$Al_2Si_2O_5(OH)_4$
10	Magnetite	Fe_2O_4
11	Muscovite	$KAl_2(AlSi_3)O_{10}(OH,F)_2$
12	Quartz	SiO_2

Table 3

Products	Associated Mineral Name
Toothpaste, Cheerios & Antacid	
Glass & Sandpaper	
Table Salt & Road Salt	
Computer hard drive	
Aluminum Foil	
Pencils	
Drywall & Plaster	
Sparkly Eye Shadow	
Pigment	
Car Battery	
Porcelain	
Copper Wire, Pennies & Matches	

Question 2. Find three ore minerals or rocks that are mined in New York State and list their uses and properties that make them useful in Table 4. Use the https://www.dec.ny.gov/docs/materials_minerals_pdf/minfactsht.pdf website for your research.

Table 4

Mineral or Rock Name	Uses	Properties that makes the mineral or rock useful

Part III. Earth materials and everyday life | What's inside my cellphone? – EXPLAIN

Earth has roughly 100 naturally occurring elements. Most rocks are made up of about eight of those elements, while smartphones use 75 of these elements! Smartphones and other electronics rely on a large number of nonrenewable elements (Fig. 9). A nonrenewable element is a substance that is being used up more quickly than it can replace itself and has a finite supply.

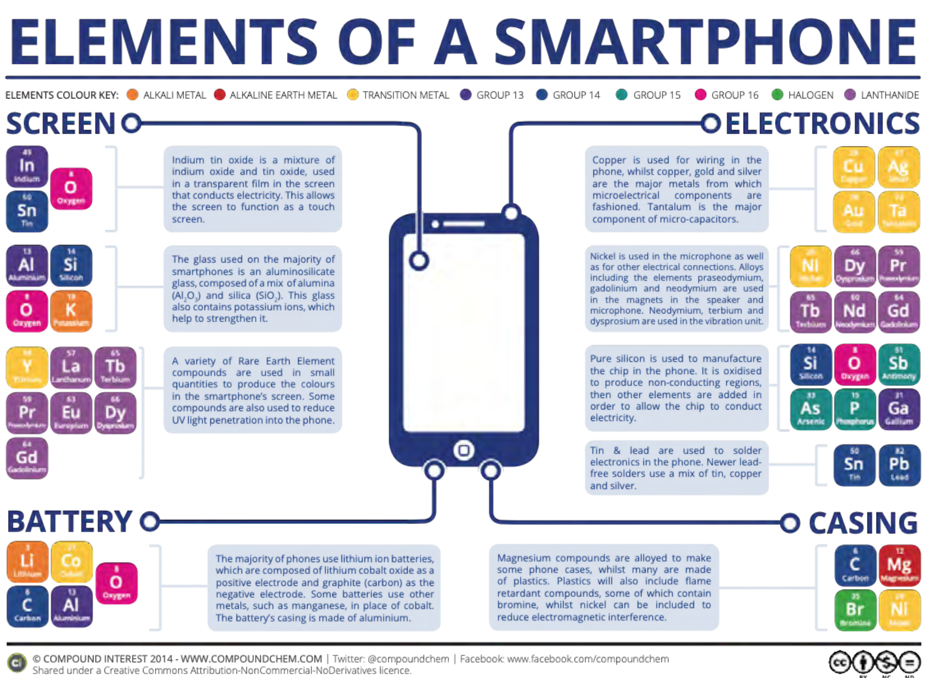


Figure 9. Some of the chemical elements that make up a cellphone.

Graphic from Compound Interest, The Chemical Elements of a Smart Phone. Licensed under CC BY-NC-ND 4.0.

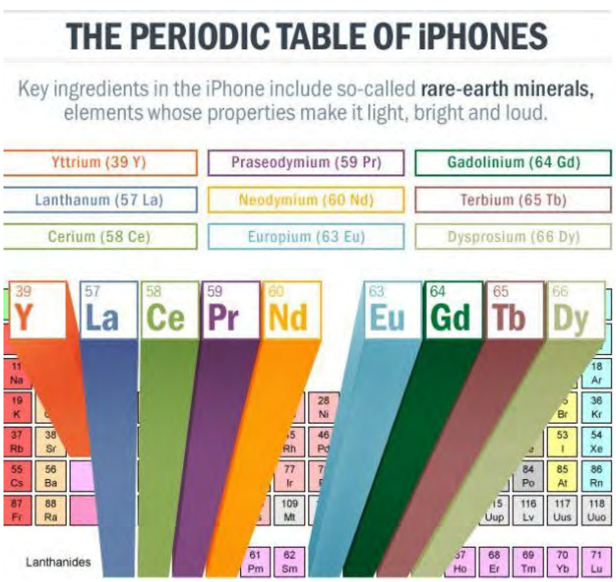
The key elements in smartphones that make them work and make them so attractive are rare earth elements (REE) (Fig. 10). As the name implies they are present on our planet in very limited supply.

Text adapted from Why it takes 75 elements to make your cell phone

They are very difficult to mine, and the mining and the processes that extract the REE from rock cause significant damage to the environment.
Roughly 85-95 percent of REE are mined in China, where relaxed environmental protection laws result in significant environmental contamination at the mine site and surrounding communities. In addition, there are dangerous and unhealthy working conditions for the miners.

These social and environmental hazards make REE "controversy minerals." The limited supply of REEs available, the difficulty of mining and refining them, and the increasing demand (about 54 percent of people globally have a cellphone, and that number is rising) have driven prices of these minerals up.

Ultimately, this increasing mineral consumption is not sustainable. Unfortunately, only REEs can do what we want electronic gadgets like cellphones and computers to do. There are no environmentally friendly or more abundant elements that can be substituted. Recycling of devices is one way to continue to meet some of the demand, but it is easy to see that if demand continues to grow, it will exceed supply in the near future.



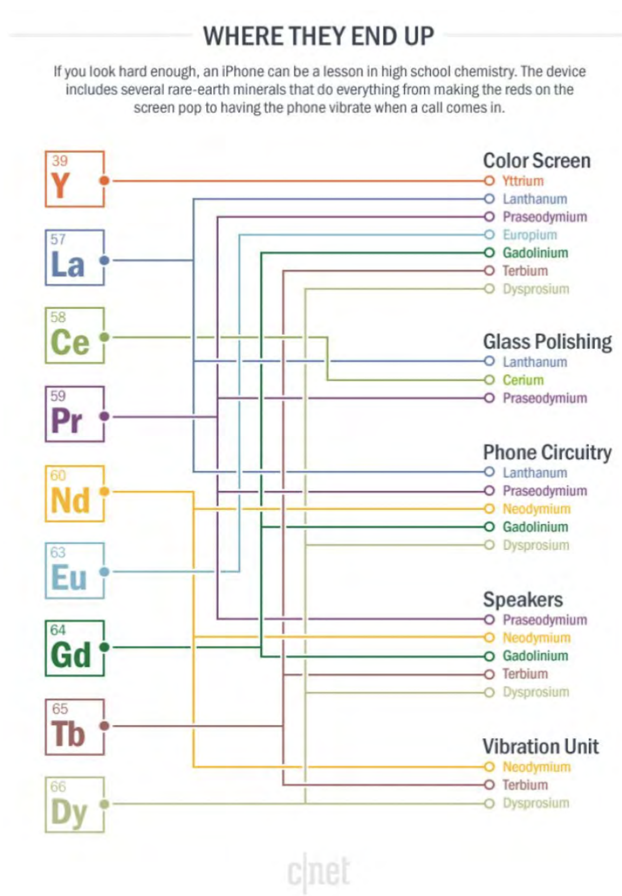


Figure 10. Rare earth elements are key components of a smart phone.

Graphics from Mark Hobbs at CNET, The Periodic Table of iPhones infographic.

Step 1. Watch Video: What's in your Smartphone? https://www.youtube.com/watch?v=66SGcBAs04w&feature=youtu.be

Step 2. Answer the following questions using the "Elements of a Smartphone" graphics (Fig. 10).

Question 1. What rare earth elements (REEs) are used in the color screens?

a. Yttrium, Lanthanum, Praseodymium, Europium, Gadolinium, Terbium, Dysprosium
b. Lanthanum, Praseodymium, Neodymium, Gadolinium, Dysprosium
c. Praseodymium, Neodymium, Gadolinium, Terbium, Dysprosium

Question 2. What rare earth elements (REEs) are used in the phone circuitry?

a. Yttrium, Lanthanum, Praseodymium, Europium, Gadolinium, Terbium, Dysprosium
b. Lanthanum, Praseodymium, Neodymium, Gadolinium, Dysprosium
c. Praseodymium, Neodymium, Gadolinium, Terbium, Dysprosium

Question 3. What rare earth elements (REEs) are used in the speakers?

a. Yttrium, Lanthanum, Praseodymium, Europium, Gadolinium, Terbium, Dysprosium
b. Lanthanum, Praseodymium, Neodymium, Gadolinium, Dysprosium
c. Praseodymium, Neodymium, Gadolinium, Terbium, Dysprosium

Step 3. Refer to the USGS Rare Earth Elements – Vital to Modern Technologies and Lifestyles handout to answer the following questions. https://pubs.usgs.gov/fs/2014/3078/pdf/fs2014-3078.pdf

Question 4. Since the 1990s how much of the world's REE production comes from China?

A. 70-80%
B. 75-85%
C. 80-90%
D. 85-95%

Question 5. Of the 15 REEs, which is most common in the Earth's crust?

A. Lanthanum (La)
B. Cerium (Ce)
C. Praseodymium (Pr)
D. Neodymium (Nd)
E. Samarium (Sm)
F. Europium (Eu)
G. Gadolinium (Gd)
H. Terbium (Tb)
I. Dysprosium (Dy)
J. Holmium (Ho)
K. Erbium (Er)
L. Thulium (Tm)
M. Ytterbium (Yb)
N. Lutetium (Lu)
O. Yttrium (Y)

Question 6. Of the 15 REEs, which is least common in the Earth's crust?

A. Lanthanum (La)
B. Cerium (Ce)
C. Praseodymium (Pr)
D. Neodymium (Nd)
E. Samarium (Sm)
F. Europium (Eu)
G. Gadolinium (Gd)
H. Terbium (Tb)
I. Dysprosium (Dy)
J. Holmium (Ho)
K. Erbium (Er)
L. Thulium (Tm)
M. Ytterbium (Yb)
N. Lutetium (Lu)
O. Yttrium (Y)

Question 7. Though some REEs are relatively abundant in the Earth's crust compared to elements such as lead and copper, what are reasons it is so difficult to mine REEs?

Question 8. Carbonatites, a rare igneous rock, have been the world's main source for light REEs since the 1960s. From what countries are REEs mined from carbonatites?

A. China
B. USA (California)
C. Australia (Western Australia)
D. All of the above

Question 9. Why has China restricted its exports of REE, and what has been the outcome of this?

A. The REE industry outside China has increased REE stockpiling.
B. It has promoted new efforts to conserve, recycle, and find substitutes for REEs.
C. New mine production has begun in Australia and the United States.
D. All of the above.

Question 10. What are some reasons is it problematic that rare earth elements (REEs) are so extensively being used in cellphones and electronics?

A. They are nonrenewable.
B. Extraction of REEs is environmentally damaging as the concentration is low, so a lot of rock must be removed from the Earth during REE mining.
C. Most of the world's population has a phone that contains REE. Phones are replaced on a regular basis.
D. All of the above.

Part IV. How long does it take mineral resources to form? – ELABORATE

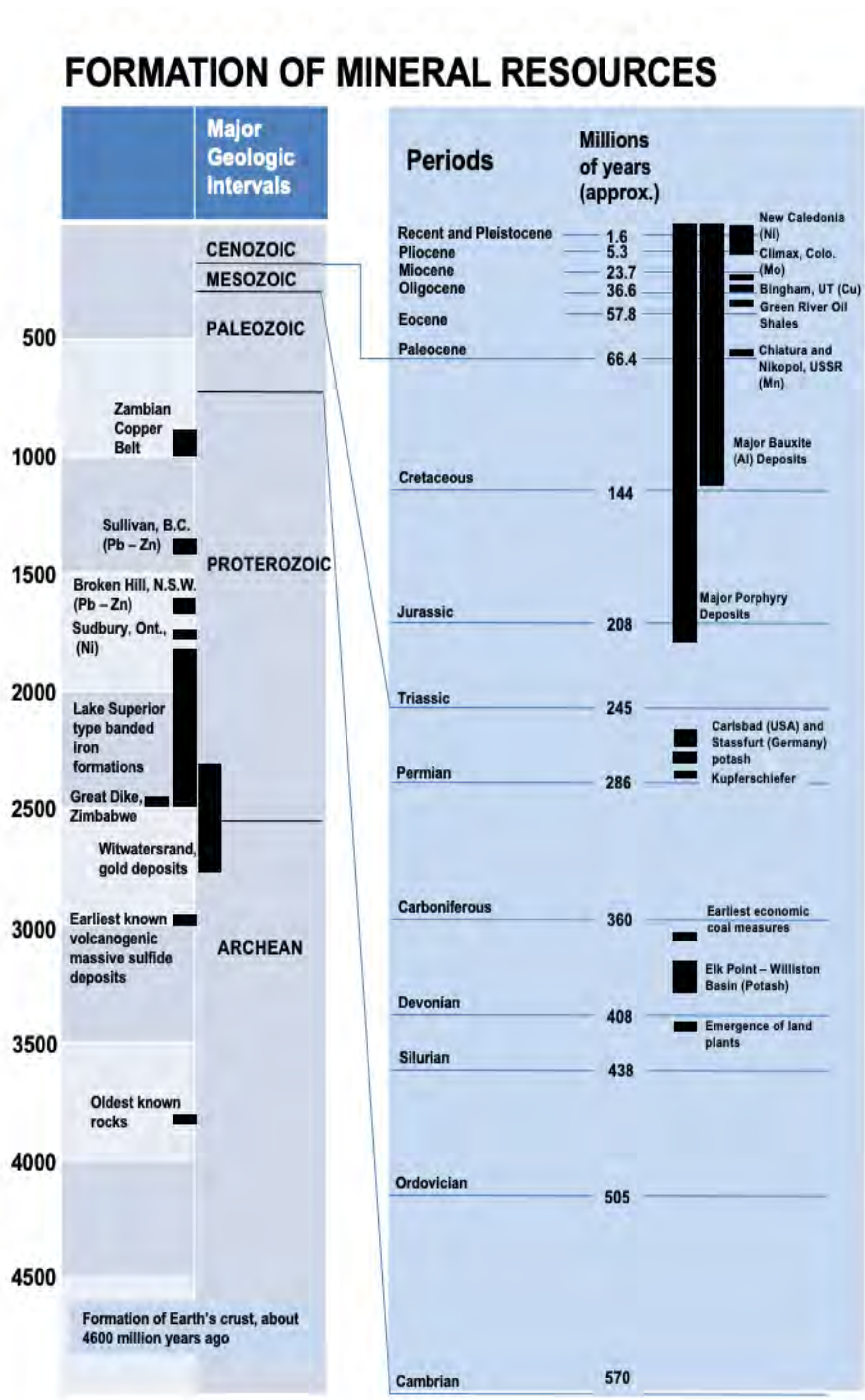
Minerals take a long time, sometimes hundreds of millions of years, to form, which is why we consider them nonrenewable.

Step 1. Use Figure 11 on the following page to answer the questions below.

Question 1. How long did it take the Witwatersrand gold deposit in Africa, the largest gold deposit in the world, to form? Witwatersrand formed between:

A. 2300-2800 Ma forming over 500 million years.
B. 1800-2500 Ma forming over 700 million years.
C. 370-380 Ma forming over 10 million years.
D. 0-142 Ma forming over 142 million years.

Figure 11. The formation of mineral resources over geological time.
Image from Heather Sloan, Lehman College, CUNY.



Question 2. How long did it take Lake Superior-type banded iron formations to form? They formed between:
A. 2300-2800 Ma forming over 500 million years.
B. 1800-2500 Ma forming over 700 million years.
C. 370-380 Ma forming over 10 million years.
D. 0-142 Ma forming over 142 million years.

Question 3. How long did it take the coal to form? It formed between:
A. 2300-2800 Ma forming over 500 million years.
B. 1800-2500 Ma forming over 700 million years.
C. 370-380 Ma forming over 10 million years.
D. 0-142 Ma forming over 142 million years.

Question 4. How long did it take major bauxite deposits to form? It formed between:
A. 2300-2800 Ma forming over 500 million years.
B. 1800-2500 Ma forming over 700 million years.
C. 370-380 Ma forming over 10 million years.
D. 0-142 Ma forming over 142 million years.

Part V. Questions – EVALUATE

Question 1. What is a mineral resource? List some ways mineral properties (e.g., hardness, conductivity) make minerals useful to humans.

Question 2. Based on what you have learned while completing this lab, what is your opinion about the relationship between our consumption of mineral resources and their abundance in nature? What effect will this have on future use of technology and digital devices?

Exercise Sources

The text and activities for Part I. Earth materials in your life and Part II. Earth materials and everyday life are adapted from Bhattacharyya, P., and Branlund, J. *Minerals and Products*. Part III. Earth materials and everyday life | What's inside my cellphone? and Part IV. How long does it take mineral resources to form? are adapted from materials created by Heather Sloan, Lehman College, CUNY.

Sources

Bhattacharyya, P., Branlund, J. Activity 1.1. *Minerals and Products*, InTeGrate. Retrieved September 4, 2020 from https://serc.carleton.edu/integrate/teaching_materials/mineral_resources/activity1-1.html

Compound Interest, The Chemical Elements of a Smart Phone, Retrieved September 4, 2020 from https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/. Licensed under CC BY-NC-ND 4.0

Mark Hobbs at CNET, The Periodic Table of iPhones infographic. Retrieved September 4, 2020 from https://www.scientificamerican.com/article/digging-for-rare-earths-the-mines-w-2012-09/

Image sources

Figure 1. By Goran tek-en, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=109449008

Figure 3, 4, 5, 7 are by J. Branlund. From Bhattacharyya, P. & Branlund, J. Activity 1.1. *Minerals and Products*, InTeGrate. Retrieved September 4, 2020 from https://serc.carleton.edu/integrate/teaching_materials/mineral_resources/activity1-1.html

Figure 2 & 8 are modified from Bhattacharyya, P. & Branlund, J. Activity 1.1. *Minerals and Products*, InTeGrate. Retrieved September 4, 2020 from https://serc.carleton.edu/integrate/teaching_materials/mineral_resources/activity1-1.html

Figure 6. By Ankur Agrawal - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=21087786

Figure 10. Mark Hobbs at CNET, The Periodic Table of iPhones infographic. Retrieved September 4, 2020 from https://www.cnet.com/news/digging-for-rare-earths-the-mines-where-iphones-are-born/

Figure 11. Heather Sloan, Lehman College, CUNY.

3. What are the different types of plate boundaries?

How was Marie Tharp instrumental in the discovery of plate tectonics?

Purpose

The purpose of this lab is to discover the types of plate boundaries through observing, describing, and classifying data.

Learning Objectives

After doing this lab you will be able to:

1. Observe patterns that occur at Earth's tectonic plate boundaries.
2. Draw the features that form at plate boundaries.
3. Explain how earth scientists classify plate boundaries.
4. Explain that plate boundaries are where the Earth is dynamic; this is where most earthquakes and volcanoes occur.

Part I. How did Marie Tharp help discover plate tectonics? – ENGAGE

Before the 1950s, little was known about the depth and structure of the ocean floor. Columbia University cartographer Marie Tharp was part of a research project to map the topography of the ocean floor. Because she was a woman, however, Tharp was not allowed to go on voyages to sea where depth measurements were made. At home in New York she plotted the sea floor depth readings.

Tharp's maps revealed underwater ridges that run along the ocean floor. Her observations led her to promote the theory of seafloor spreading – the idea that the continents move apart due to new seafloor being created at volcanic ridges in the middle of ocean basins. This was a huge contribution to the development of the theory of plate tectonics.

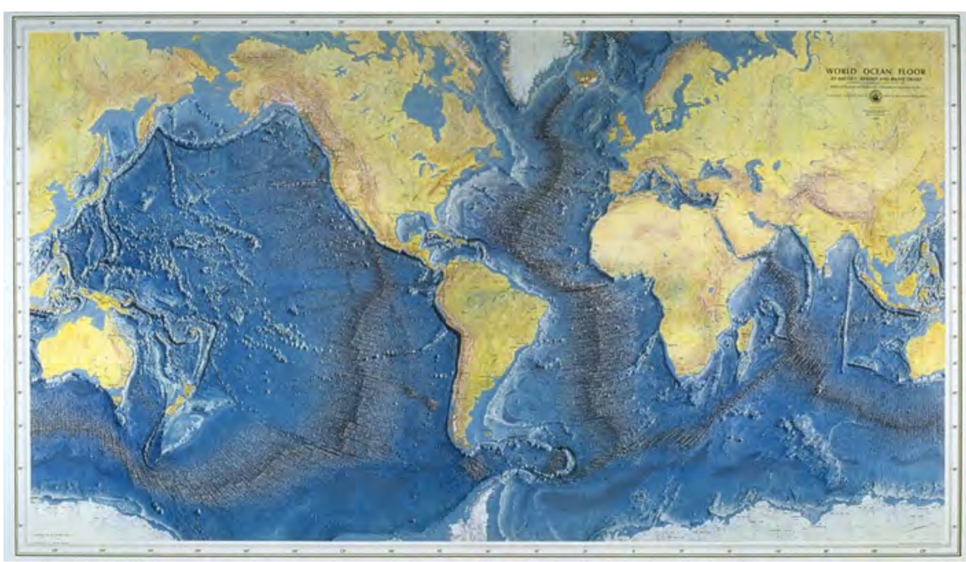


Figure 1. Marie Tharp's 1977 World Ocean Floor map. Copyright by Marie Tharp 1977/2003.

Question 1. Observe Marie Tharp's 1977 World Ocean Floor map. What are some questions you have about this map?

Part II. Explore the evidence that led to the theory of Plate Tectonics Map Activity – EXPLORE

Materials needed

1. Instruction sheet
2. Two plate boundary maps
3. Colored pencils
4. Four specialty maps

Question 1. Look at the handout of the plate boundary map with the black lines. What do you think the lines represent? Are they all showing the same thing?

In this exercise you are given four data maps that contain information about plate tectonic processes on Earth. These data have been acquired over many years by many scientists. Scientists developing the key ideas of plate tectonics over the past 40 years had only fragments of these data to work with as they tried to describe, classify, and interpret what they saw.

Map 1 shows earthquake locations and depths. The location of each earthquake is indicated by a small dot, and its depth is indicated by the color of the dot.

- **Red** dots indicate shallow earthquakes with depths between zero and 33 km.
- **Yellow** or orange dots indicate intermediate earthquakes with depths between 33 and 70 km.
- **Green** dots indicate deep earthquakes having depths between 70 and 300 km.
- **Blue** dots indicate ultra-deep earthquakes with depths between 300 and 700 km.

Map 2 shows the locations of geologically recent (in the past 10,000 years) volcanic features on the Earth. The dots represent volcanoes, geysers, and hot springs.

Map 3 shows the age of the oceanic crust under most of the world's oceans. This map highlights divergent plate boundaries, also known as mid-ocean ridges or spreading centers. The scale bar on the right shows how the colors correspond to age of the seafloor in millions of years. Red signifies the youngest crust. Blue signifies the oldest oceanic crust.

Map 4 shows the elevation of the land surface (topography) and the depth of the oceans (bathymetry). The map uses color to indicate varying elevation and depth. The scale bar on the right shows how colors on the map correspond to elevation in meters.

Step 1. Take out your two copies of the plate boundary maps and the scientific specialty maps.

Step 2. Look at Map 1 showing **earthquake data**. Look for distribution patterns. Focus your attention on the distribution of earthquakes at plate boundaries.

Question 2. Can you identify different types of plate boundaries based on the earthquake patterns and depths? Explain.

Step 3. Look at Map 2 showing **volcano data**. Look for distribution patterns. Focus your attention on the distribution of volcanoes at plate boundaries.

Question 3. Can you identify different types of plate boundaries based on volcano data? Explain.

Step 4. Look at Map 3 showing the ages of the oceanic crust on the seafloor. Look for distribution patterns.

Question 4. Can you identify different types of plate boundaries based on the seafloor age data? Explain.

Step 5. Look at Map 4 showing the Earth's topography and bathymetry. Look for distribution patterns.

Question 5. Can you identify different types of plate boundaries based on surface elevation data? Explain.

Step 6. Focus your attention on the plate boundaries.

- Label one of the two plate boundary maps as Map 1. Using this map, identify the nature of your data near the plate boundaries. Is the land high or low, symmetric or asymmetric, missing or not missing, varying along the boundary or constant along the boundary?
- Based on your observations, classify the plate boundaries on Map 1. Restrict yourself to about 4-5 boundary types (e.g., Type 1, Type 2 etc.). At this point, do not try to explain the data; just observe!

Step 7. Assign a colored pencil color to each boundary type in your classification scheme.

- Color your first Plate Boundary Map to represent your boundary types.
- Write down descriptions of the plate boundary classifications on the back of their map. These maps and descriptions will be turned in at the end of the exercise.

Step 8. Discuss the three types of plate boundaries with your instructor

Part III. Explore the evidence that led to the theory of Plate Tectonics – EXPLAIN

Plate Tectonics Introduction

Scientists now have a fairly good understanding of how the plates move and how such movements relate to earthquake activity. Most movement occurs along narrow zones between plates where the results of plate-tectonic forces are most evident.

There are three types of plate boundaries (Fig. 2):

1. **Convergent boundaries:** where lithosphere is destroyed as one plate dives under another.
2. **Divergent boundaries:** where new lithosphere, or a rigid layer made up of the crust and uppermost mantle and also known as a tectonic plate, is generated as the plates pull away from each other.
3. **Transform boundaries:** where lithosphere is neither created nor destroyed as the plates slide horizontally past each other.

Text modified from USGS *Understanding Plate Motions*
What are the different types of plate boundaries?

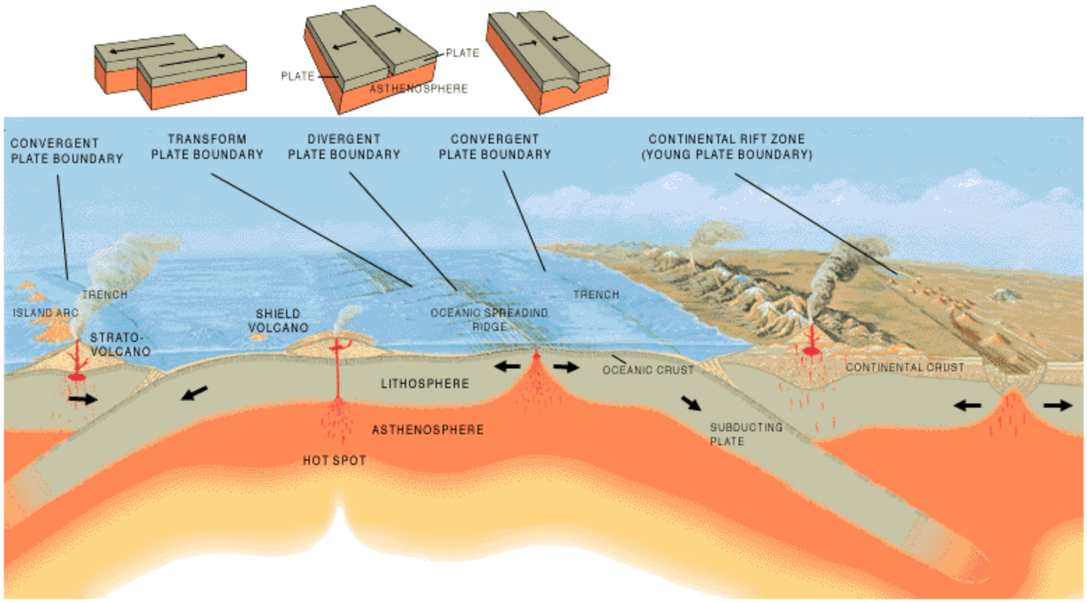


Figure 2. A cross section of the Earth showing the three types of plate boundaries. The lithosphere, or plate, is a rigid layer of rock made up of the crust and uppermost mantle. The asthenosphere is a more plastic layer of mantle rock below the lithosphere which accommodates the movement of the plates. From USGS

Divergent boundaries

Divergent boundaries occur along spreading centers where plates are moving apart and new crust is created by magma pushing up from the mantle. You can imagine this as two giant conveyor belts, facing each other but slowly moving in opposite directions as they transport newly formed oceanic crust away from the ridge crest.

Convergent boundaries

The Earth's unchanging size implies that the crust must be destroyed at about the same rate as it is being created. Such destruction (recycling) of crust takes place along convergent boundaries where plates are moving toward each other, and sometimes one plate sinks or is subducted under another. The location where sinking of a plate occurs is called a **subduction zone**. Convergence can occur:

1. between an oceanic and a largely continental plate, or
2. between two largely oceanic plates, or
3. between two largely continental plates.

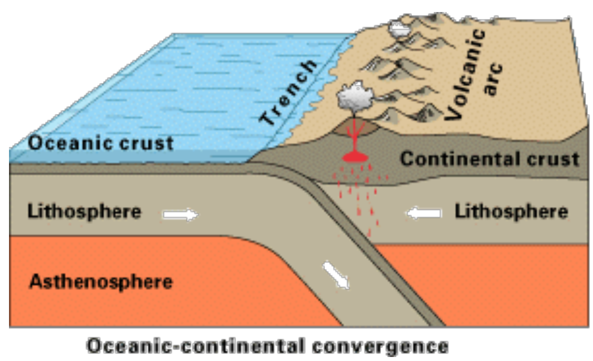


Figure 3. Convergence of an oceanic plate and a continental plate. The oceanic plate on the left is subducting under the continental plate. From USGS

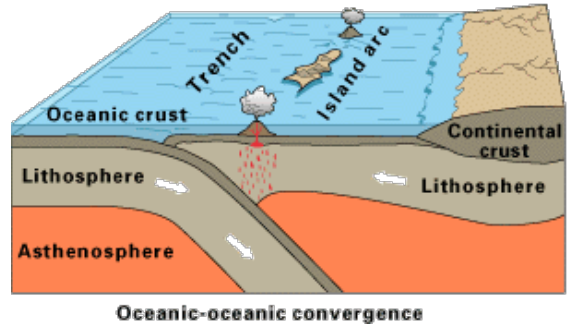
Oceanic-continental convergence

On the edges of continents, long, narrow, curving trenches thousands of kilometers long and 8 to 10 km deep cut into the ocean floor. Trenches are the deepest parts of the ocean floor, and they are created by subduction. Subduction is when one oceanic lithospheric plate dives under the other and is pushed into the Earth.

Text modified from USGS *Understanding Plate Motions*
What are the different types of plate boundaries?

The overriding plate is lifted up creating towering volcanic mountains. Strong, destructive earthquakes are also common (Fig. 3).

Figure 4. Convergence of two oceanic plates. A chain of volcanoes called an island arc forms above the subduction zone. From USGS



Oceanic-oceanic convergence

When two oceanic plates converge, the denser plate is usually pushed under the other, and in the process a trench is formed (Fig. 4).

The Marianas Trench (paralleling the Mariana Islands), for example, marks where the Pacific Plate converges against the Philippine Plate. The Challenger Deep, at the southern end of the Marianas Trench, plunges more deeply into the Earth's interior (nearly 11,000 m) than Mount Everest, the world's tallest mountain, rises above sea level (about 8,854 m; Fig. 5).

Subduction processes also result in the formation of chains of volcanoes that closely parallel trenches. For oceanic-oceanic collisions, such volcanoes are typically strung out in chains called island arcs. Magmas that form island arcs are produced by the partial melting of the descending plate and/or the overlying oceanic lithosphere. The descending plate also provides a source of stress as the two plates interact, leading to frequent earthquakes.

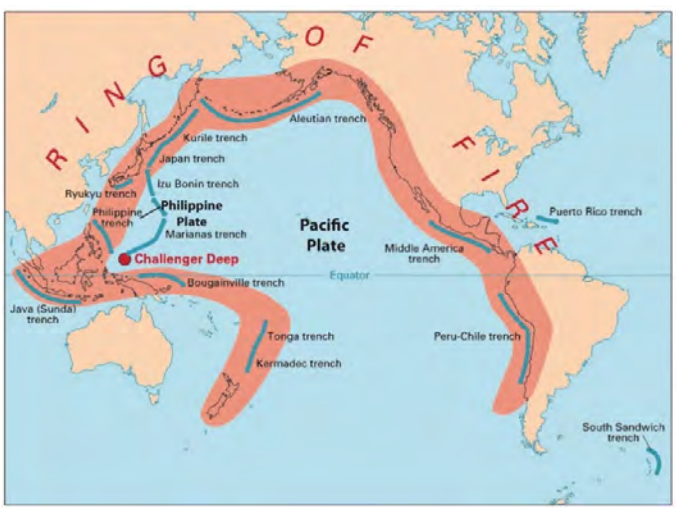
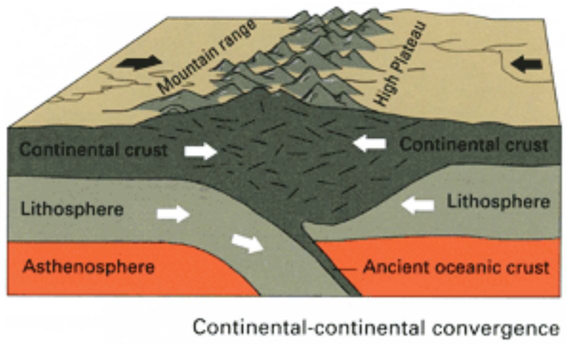


Figure 5. Volcanic arcs and oceanic trenches partly encircling the Pacific Basin form the so-called Ring of Fire, a zone of frequent earthquakes and volcanic eruptions. The trenches are shown in blue-green. The volcanic island arcs are parallel to, and landward of, the trenches. For example, the island arc associated with the Aleutian Trench is represented by the long chain of volcanoes that make up the Aleutian Islands. Modified from USGS

Continental-continental convergence

When two continents meet head-on, neither is subducted because the continental rocks are relatively light and, like two colliding icebergs, resist downward motion. Instead, the crust tends to buckle and be pushed upward or sideways. The collision of India into Asia 50 million years ago caused the Indian and Eurasian Plates to crumple up along the collision zone. After the collision, the slow continuous convergence of these two plates over millions of years pushed up the Himalayas and the Tibetan

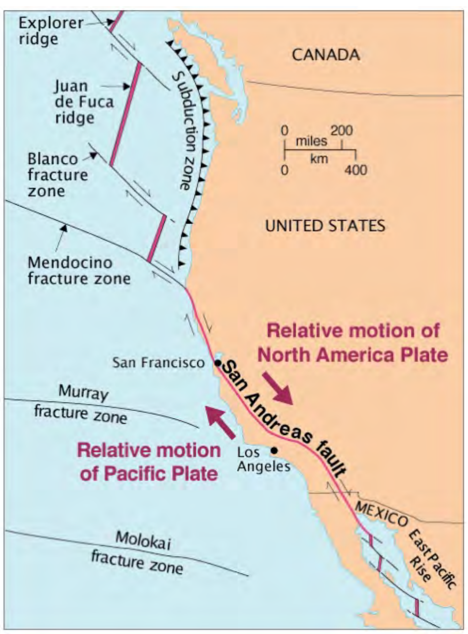


Plateau to their present heights (Fig. 6). The Himalayas, towering as high as 8,854 m above sea level, form the highest continental mountains in the world.

Figure 6. The collision between the Indian and Eurasian plates has pushed up the Himalayas and the Tibetan Plateau. From USGS

Transform boundaries

The zone between two plates sliding horizontally past one another is called a transform-fault boundary, or a transform boundary. Most transform faults are found on the ocean floor. They commonly offset the active spreading ridges, producing zig-zag plate margins, and are generally defined by shallow earthquakes. However, a few occur on land; for example, the San Andreas fault zone in California. This transform fault connects the East Pacific Rise, a divergent boundary to the south, with the South Gorda – Juan de Fuca – Explorer Ridge, another divergent boundary to the north (Fig. 7).



The San Andreas fault zone (Fig. 7), which is about 1,300 km long and in places tens of kilometers wide, slices through two-thirds of the length of California. Along it, the Pacific Plate has been grinding horizontally past the North American Plate for 10 million years, at an average rate of about 5 cm per year. Land on the west side of the fault zone (on the Pacific Plate) is moving in a northwesterly direction relative to the land on the east side of the fault zone (on the North American Plate).

Figure 7. The San Andreas fault zone is one of the few transform faults exposed on land. The Blanco, Mendocino, Murray, and Molokai fracture zones are some of the many transform faults that scar the ocean floor and offset spreading ridges. From USGS

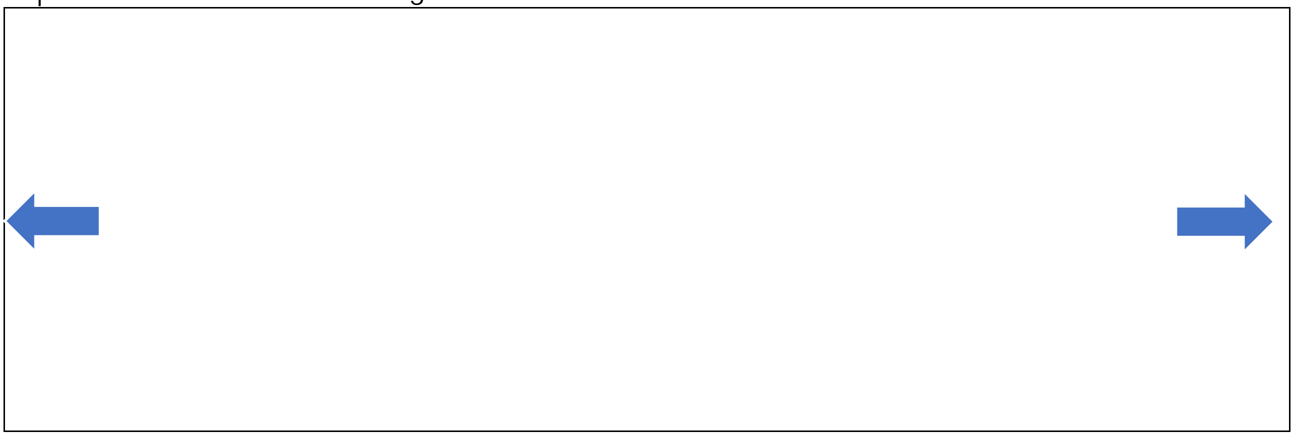
Rates of motion

Because plate motions are global in scale, they are best measured by satellite-based methods. The Arctic Ridge has the slowest rate (less than 2.5 cm per year), and the East Pacific Rise near Easter Island, in the South Pacific about 3,400 km west of Chile, has the fastest rate (more than 15 cm per year).

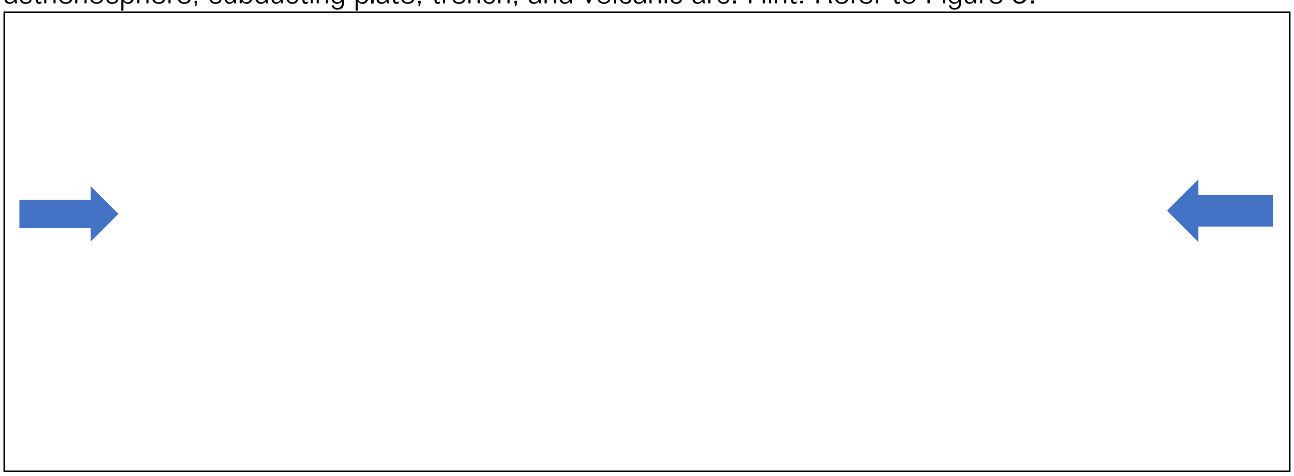
Step 9. On your second plate boundary map, classify the plate boundaries based on your discussion with your instructor. Also write a description of the plate boundary classes you have used.
Step 10. Upload a photo of your two plate boundary maps in Blackboard.

Part III. Draw Plate Boundaries – EXPLAIN

Question 1. Draw a cross-section of a divergent plate boundary. Label the lithosphere, asthenosphere oceanic crust, mid-ocean ridge, and upwelling magma. The arrows show the direction of plate motion. Hint: Refer to Figure 2.



Question 2. Draw a cross-section of a convergent plate boundary. Label the lithosphere, asthenosphere, subducting plate, trench, and volcanic arc. Hint: Refer to Figure 3.



Question 3. Draw a cross-section of a transform plate boundary. Label the lithosphere and fault. Hint: Refer to Figure 8.

Part IV. Plate Boundaries using Google Earth – ELABORATE

Step 1. Open your web browser and launch Google Earth: https://www.google.com/earth/

Question 1. Explore the topography of the Earth's surface above sea level. Are mountains randomly distributed on the continents, or do they tend to occur in particular patterns (clusters, linear chains, arcs, etc.)?

Question 2. Look up and provide the elevation of Mount Everest, the highest point on earth.

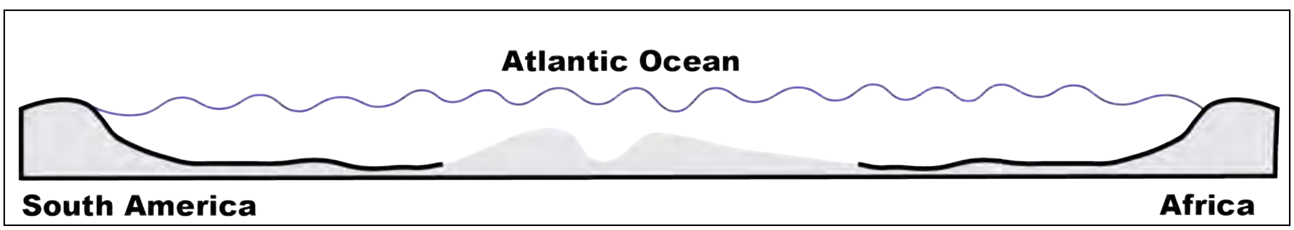
________feet, _________meters

Question 3. Explore the bathymetry of the Earth's surface below sea level. On Google Earth, the bathymetry of the ocean floor is shown with shades of blue; the darker the blue the deeper the water.

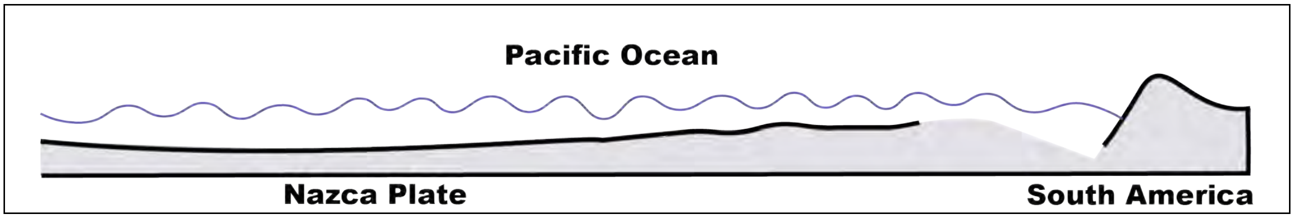
Examine the Atlantic Ocean between South America and Africa. Does it have a smooth bottom? Does depth increase or decrease toward the middle? What is the bathymetry that you find in the middle of the Atlantic Ocean (a plain, a valley, a mountain chain, etc.)?

A. A flat plain.
B. A mountain chain or ridge with a deeper valley running through it.
C. A deep trench near a chain of islands or a continent.

Question 4. Features like the one running down the middle of the Atlantic Ocean are called mid-ocean ridges or spreading ridges. Zoom in to see that although the ridge is a topographic high, it also has a valley, known as a rift valley, running along the middle of it. In the space below, complete the topographic profile of the Atlantic Ocean floor between South America and Africa. Label the rift valley.



Question 5. The Earth's lowest spots aren't in the middle of the ocean, so where are they? Look at the west coast of South America, and in the space below complete the topographic profile of the Pacific Ocean floor from South America westward about 600 miles (1000 km). Label the trench where the oceanic plate is subducting beneath another plate.



Question 6. The deep linear features near a chain of islands or a continent are called ocean trenches. Using Google Earth, "fly to" Challenger Deep, the deepest place on Earth (once Google Earth gets you there, you may have to zoom out to see where you are). Where is it?

A. Hawaii
B. East Pacific Rise
C. Mariana Trench
D. Kermadec Trench

Question 7. Challenger Deep reaches 11 km (36,000 ft) below sea level. Which is greater, the elevation of Mount Everest (see question 2) above sea level, or the depth of Challenger Deep below sea level, and by how much? Does this surprise you?

A. Mount Everest above sea level is greater
B. Challenger Deep below sea level is greater

Question 8. Find your current location on your map. Where is nearest divergent plate boundary where there is a mid-ocean ridge?

A. Mid-Atlantic Ridge
B. Puerto Rico Trench
C. East Pacific Rise
D. Aleutian Trench

Question 9. Where is the nearest convergent boundary where there is a subduction zone and trench?

A. Mid-Atlantic Ridge
B. Puerto Rico Trench
C. East Pacific Rise
D. Aleutian Trench

Question 10. Where is the nearest transform plate boundary?

A. Mid-Atlantic Ridge
B. Puerto Rico Trench
C. East Pacific Rise
D. San Andreas Fault Zone

Part VI Questions – EVALUATE

Question 1. What type of crust forms where plates move apart at divergent boundaries?

A. Continental
B. Oceanic
C. None of the above

Question 2. Where do the youngest rocks occur on the sea floor?

A. At the mid-ocean ridges in the center of the ocean basins
B. On the edges of the ocean basins
C. The oceanic crust is all the same age.

Question 3. Where do subduction zones form?

A. At divergent plate boundaries
B. At convergent plate boundaries
C. At transform plate boundaries

Question 4. Where do volcanoes and earthquakes related to plate motions occur?

A. At divergent plate boundaries
B. At convergent plate boundaries
C. At transform plate boundaries
D. Both a and b are correct.
E. Choices a, b, and c are correct.

Question 5. The Himalaya mountains formed as a result of:

A. Continental-oceanic plate collision
B. Oceanic-oceanic plate collision
C. Continental-continental plate collision

Question 6. Which choice is correct regarding the mid-ocean ridges that form chains of volcanoes across the ocean floor?

A. Form the deepest region of the ocean floor.
B. Form some of the tallest parts of the ocean floor.
C. Form the flattest parts of the ocean floor.

Question 7. Which choice is correct regarding trenches that mark the place where one tectonic plate is diving under another at a subduction zone?

A. Form the deepest region of the ocean floor.
B. Form some of the tallest parts of the ocean floor.
C. Form the flattest parts of the ocean floor.

Question 8. The Pacific Ring of Fire is:

A. A zone of frequent fires encircling the Pacific Ocean basin.
B. A zone of frequent earthquakes and volcanic eruptions encircling the Pacific Ocean basin.
C. Along a divergent boundary.
D. Along a transform plate boundary.

Exercise sources

Part II is adapted from Discovering Plate Boundaries by Dale Sawyer. Much of the explanation text in Part III. Explore the evidence that led to the theory of Plate Tectonics Map Activity is modified from This Dynamic Earth [USGS]. Part IV. Plate Boundaries using Google Earth is adapted from Goodell 2013.

Sources

This Dynamic Earth [USGS]. (5 May 1999). Retrieved January 7, 2022, from https://pubs.usgs.gov/gip/dynamic/dynamic.html#anchor19309449

Sawyer, D. (16 May 2002). Discovering Plate Boundaries. Retrieved January 7, 2022, from https://plateboundary.rice.edu/intro.html

Goodell, L. (2013, February). Using Google Earth to explore plate tectonics. Examples. Retrieved January 7, 2022, from https://serc.carleton.edu/sp/library/google_earth/examples/49004.html

Image sources

Figure 1. *World Ocean Floor Panorama*, Authors Marie Tharp and Bruce C. Heezen, 1977. Copyright by Marie Tharp 1977/2003. Reproduced by permission of Marie Tharp Maps, LLC, 8 Edward Street, Sparkill, New York 10976.

Figures 2-7. *This Dynamic Earth USGS.* 5 May 1999 <https://pubs.usgs.gov/gip/dynamic/dynamic.html>

PLATE BOUNDARY MAP

This map is from Dietmar Mueller, Univ. of Sydney

This map is part of "Discovering Plate Boundaries," a classroom exercise developed by Dale S. Sawyer at Rice University (dale@rice.edu). Additional information about this exercise can be found at http://terra.rice.edu/plateboundary .

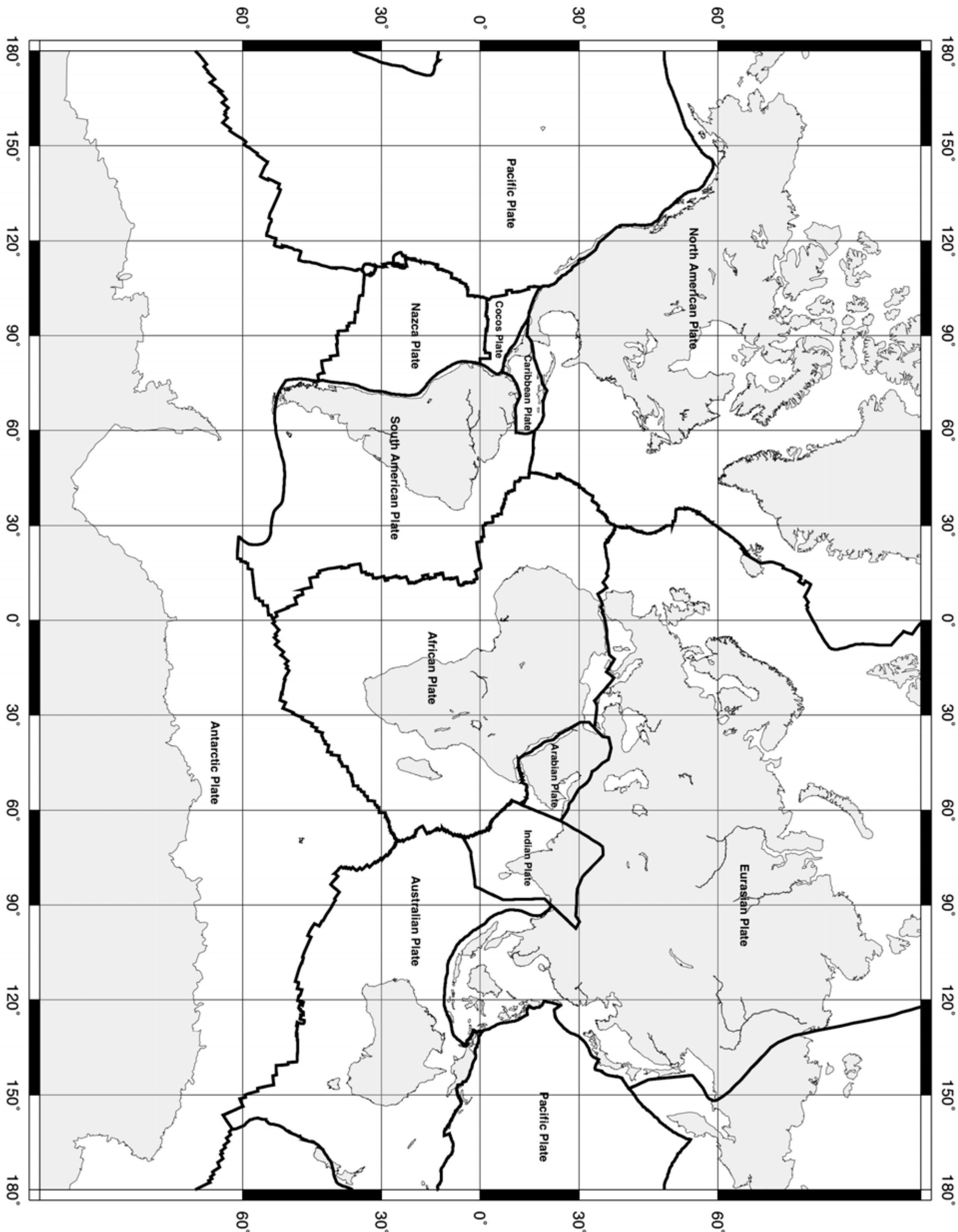
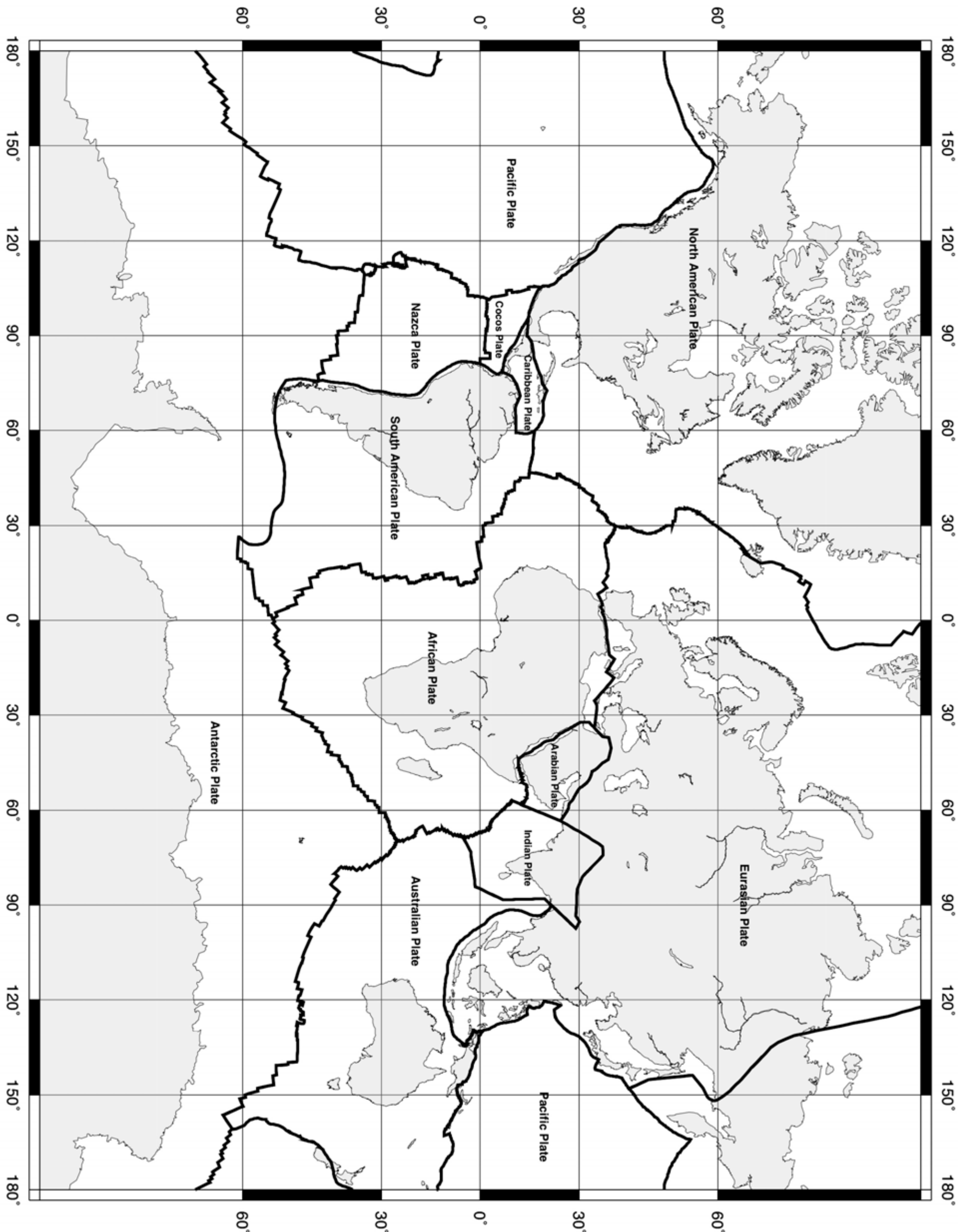


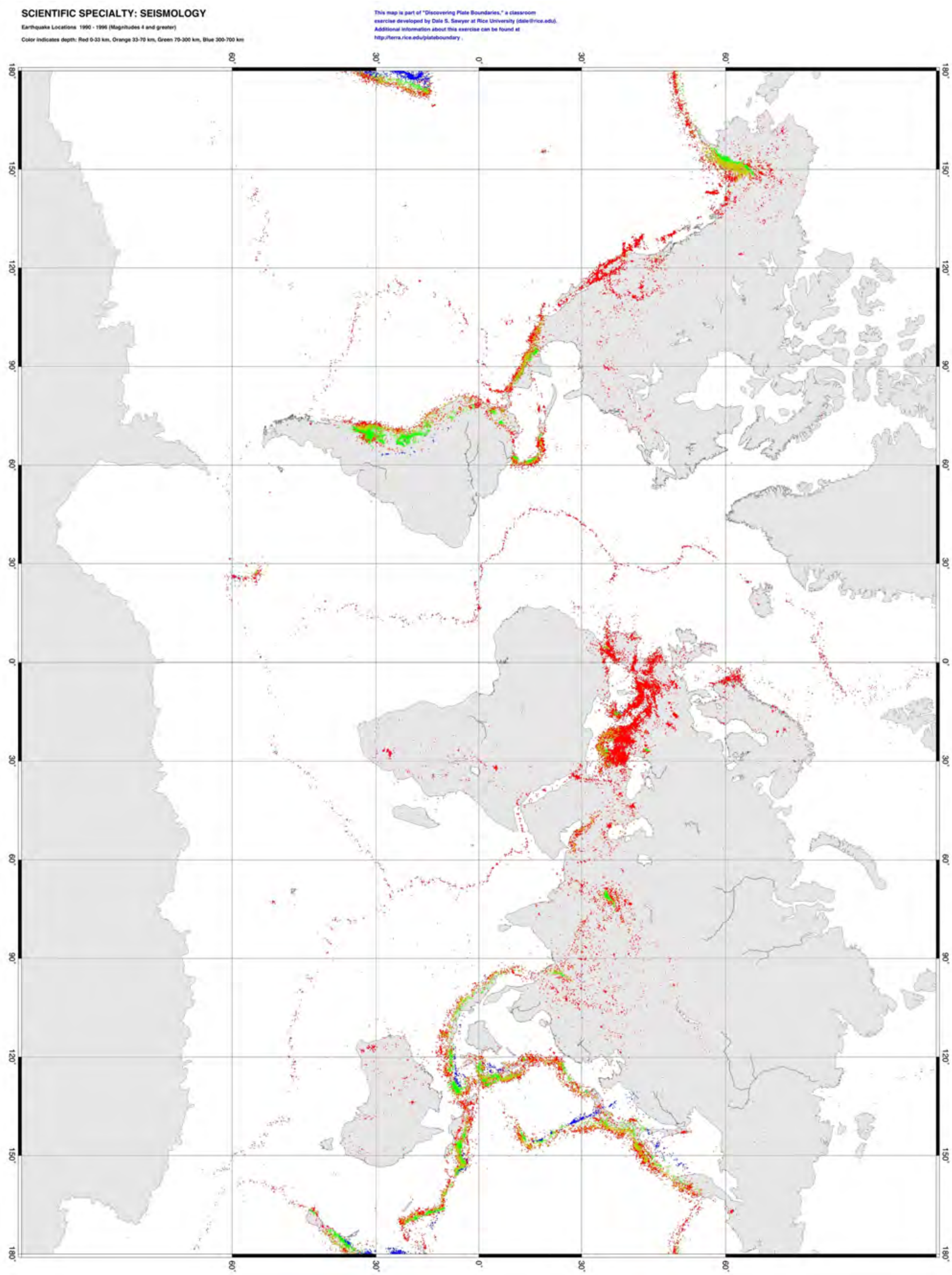
PLATE BOUNDARY MAP

This map is from Dietmar Mueller, Univ. of Sydney

This map is part of "Discovering Plate Boundaries," a classroom exercise developed by Dale S. Sawyer at Rice University (dale@rice.edu). Additional information about this exercise can be found at http://terra.rice.edu/plateboundary .

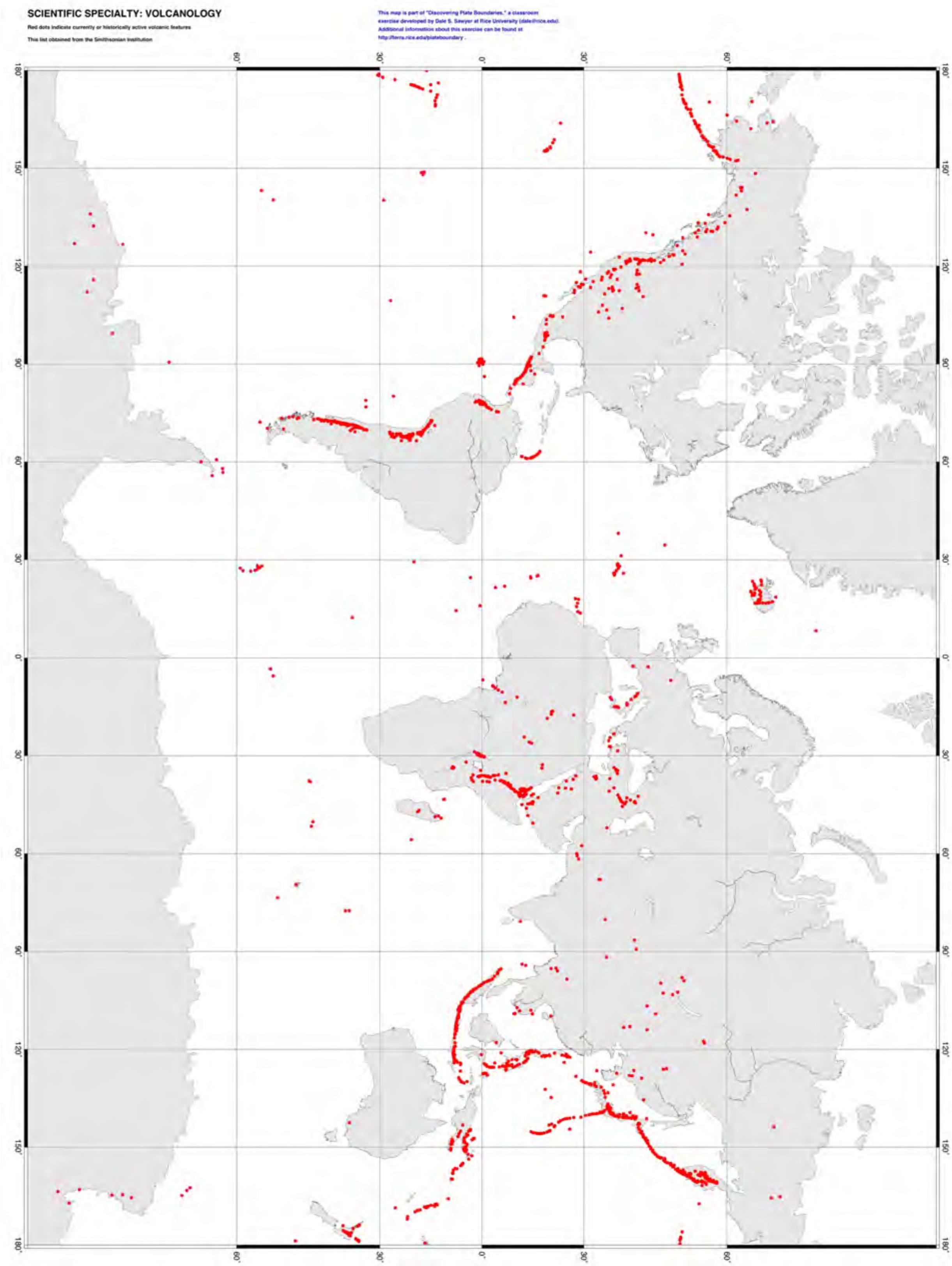


Map 1 - Earthquakes

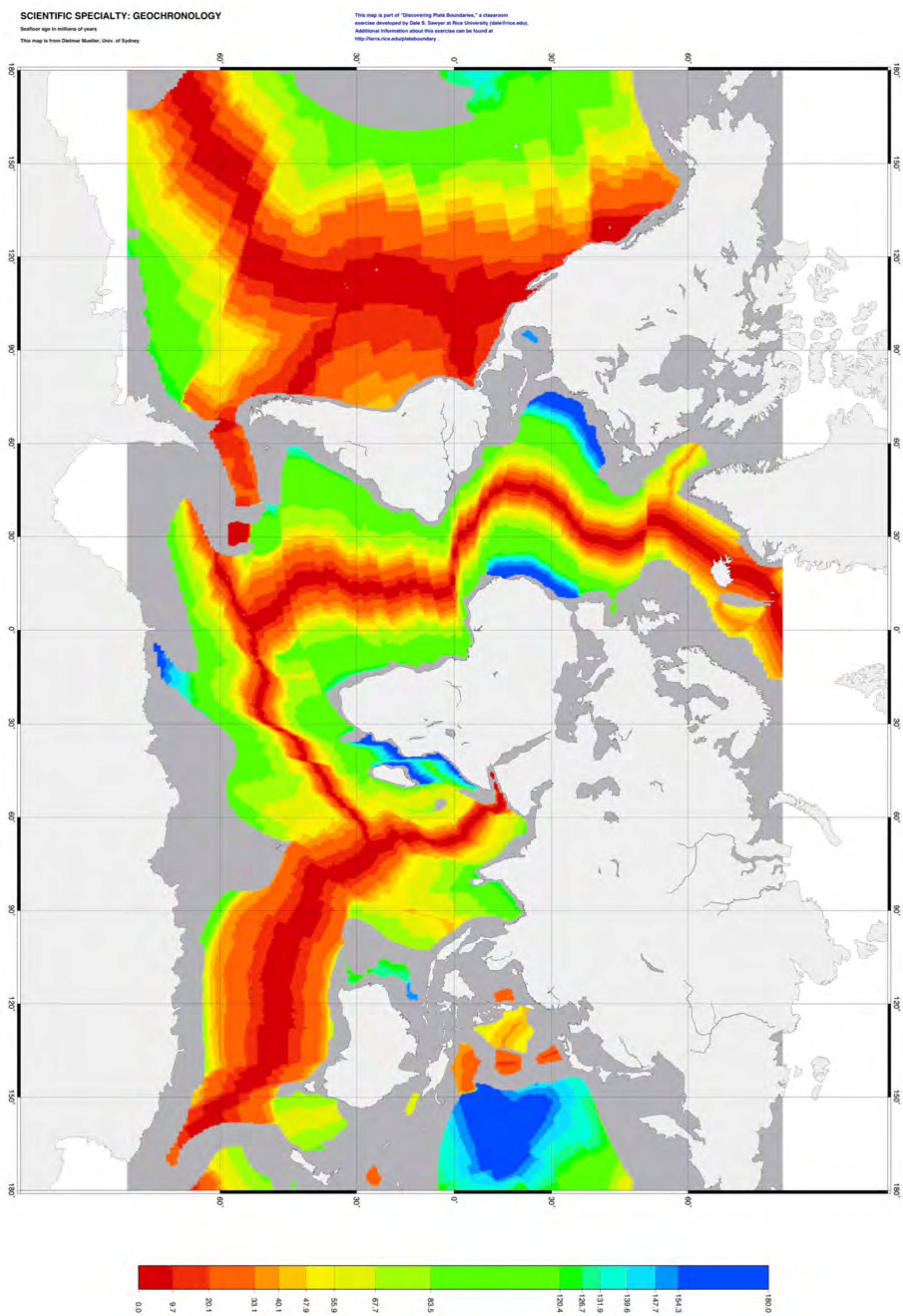


What are the different types of plate boundaries?

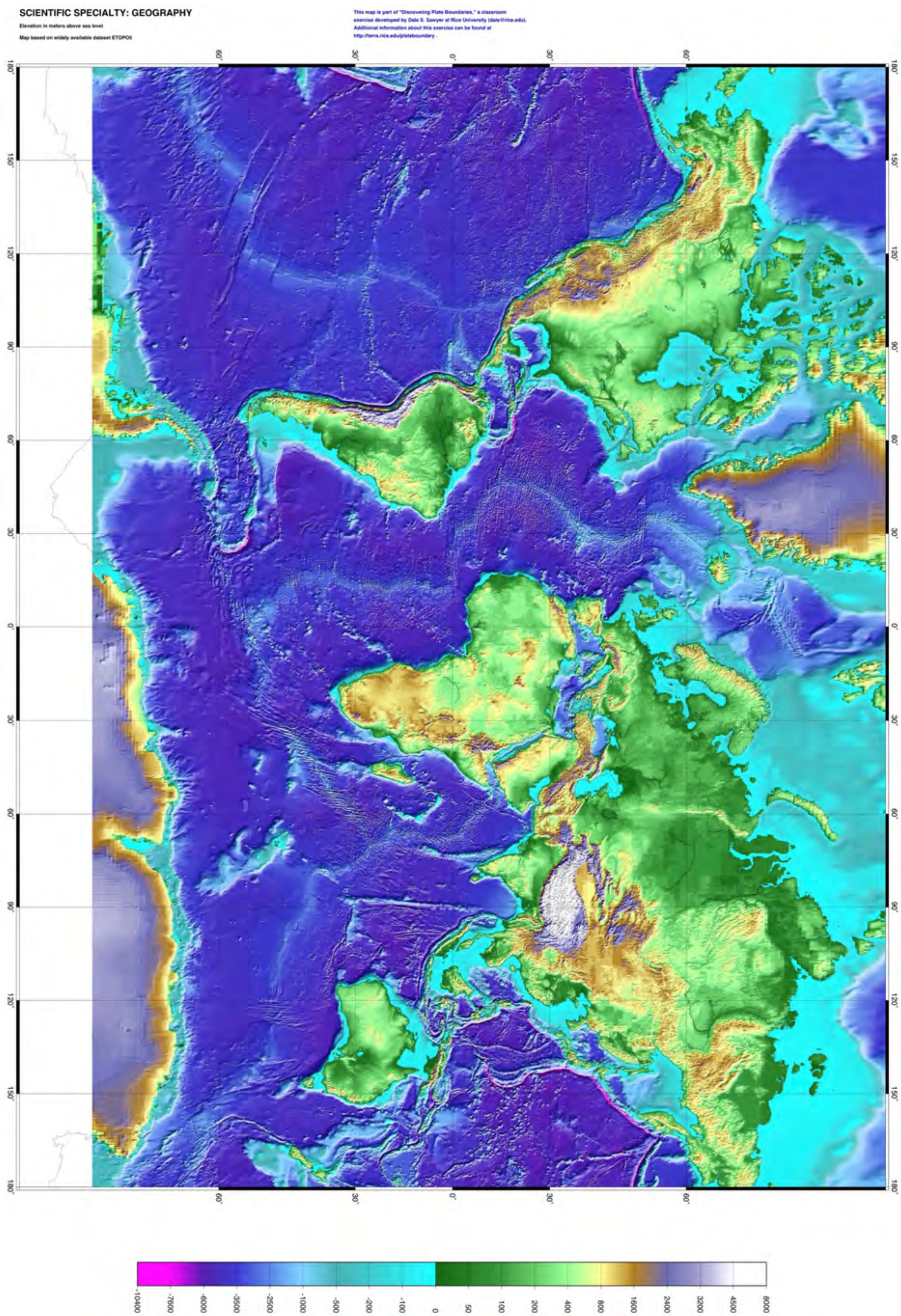
Map 2 - Volcanism



Map 3 – Paleomagnetism



Map 4 – Bathymetry/Topography



4. How do we classify igneous rocks, and where do they form?

How are the crystalline rocks of the Palisades and the bear den different?

Introduction

Igneous rock (from the Latin word *ignis* for fire) is one of the three main types of rocks (the others being sedimentary and metamorphic rocks). Igneous rocks form when molten magma inside the Earth, near active plate boundaries or hotspots, rises towards the surface and cools. Mineral crystals and, sometimes, glass solidify from the magma to form a rock.

Purpose

In the following exercises you will become familiar with the compositions and cooling histories of igneous rocks. You will learn how to identify common igneous rocks based on color and texture, determine the mineral make-up of common igneous rocks, and determine the relationships between igneous rock compositions and tectonic setting.

Learning objectives

After doing this lab you will be able to:

1. Explain how igneous rocks form underground and above ground.
2. Explain how to determine the cooling history of igneous rocks based on rock texture.
3. Explain how to determine the composition of igneous rocks based on rock color.
4. Explain how igneous rocks of the same composition but different cooling histories have different textures but the same distribution of minerals.
5. Explain the relationship between igneous rock composition and tectonic setting.

Materials needed

- Images or specimens of 10-12 common igneous rocks (see appendix 1 for rock images)

Part I. How are the crystalline rocks of the Palisades and the bear den different? – ENGAGE

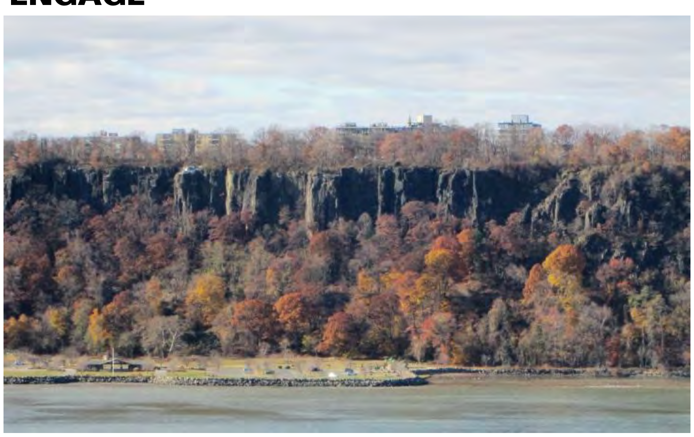


Figure 1. (a) The Palisades Sill in New Jersey (left). From Beyond My Ken, CC BY-SA 4.0. (b) Bear den granite, Bronx Zoo (right). From Harvey Barrinson, Bronx Zoo 2015 05 24 0141, CC BY-NC-SA 2.0

Question 1. The Palisades Cliffs are part of a layer of dark, finely crystallized volcanic rock that towers about 600 feet above the west side of the Hudson River and is about 200 million years old. The bear den granite is a pink, coarsely crystalline intrusion of igneous rock in the bear enclosure at the Bronx Zoo. It is about 350 million years old. What was New York like when these igneous rocks were forming?

Question 2. Examine the igneous rocks. List some ways to divide these rocks into groups or categories. Compare your classification scheme to other students' schemes. Add any categories that the other students used that you had not thought about.

Rock Numbers	Grouping

About igneous rocks

Igneous rocks are divided into two groups, **intrusive or extrusive**, depending upon where the molten magma solidifies to rock. If this molten fluid extrudes (pushes out) as lava at Earth's surface or as fragmental material from an explosive volcanic eruption, it forms an extrusive igneous rock. If the magma cools and solidifies inside the Earth, it forms an intrusive or plutonic igneous rock.

Igneous rocks can be classified by their **crystal size** and **chemical composition**, both of which tell us about their origin.

Part II. Introduction to igneous rocks – EXPLORE

Step 1. Your instructor will introduce igneous rock textures and color (composition) with a slide presentation. You can also find this information below.

Igneous rock textures

Texture refers to the way the mineral grains fit together. The texture of an igneous rock reflects its cooling history but may also be influenced by its chemical composition. Rocks that cooled slowly underground (intrusive or plutonic) have visible crystals. Rocks that cooled rapidly above ground (extrusive or volcanic) have very small crystals.

1. **Phaneritic** texture is found in intrusive rocks in which crystals are visible, interlocking, and the same general size. Most igneous rocks have phaneritic textures.
2. **Aphanitic** texture is found in extrusive rocks. The crystals in the rock are too small to identify without magnification.
3. **Porphyritic** texture refers to large crystals (phenocrysts) surrounded by a fine-grained or aphanitic material (the groundmass). This indicates two rates of cooling with visible crystals cooling slowly and the finer groundmass cooling rapidly.
4. **Glassy** texture is a rock without crystals and indicates formation from lava that cooled so quickly at the Earth's surface that no crystals had a chance to form. Glasses, like the rock obsidian, are dark in color due to impurities rather than the presence of dark colored minerals.
5. **Vesicular** rocks contain bubbles or holes (vesicles) that formed when hot gas bubbles were trapped in the lava as it cooled. Vesicular rocks are made of tiny glass particles and some minerals.
6. **Tuff** is a consolidated (hardened and/or compacted) pyroclastic (explosive, volcanic origin) rock. They are made up of a mix of glass shards, fragments of crystals, and small pieces of pre-existing (often aphanitic) igneous rock, commonly welded together.

Question 1. Group igneous rocks by texture in Table 1 (below).

Table 1.

Type	Intrusive	Extrusive				
Texture	**Phaneritic**	**Aphanitic**	**Porphyritic**	**Vesicular**	**Glassy**	**Pyroclastic**
Rock Number						

Igneous rock compositions

The chemical composition of an igneous rock is what determines its color and whether it is dark or light. Igneous rock compositions can be divided into three main types (Fig. 1):

1. **Felsic rocks** are light-colored (white, tan, pink, light grey) due to being high in the chemical elements silicon, potassium, and aluminum, and low in iron and magnesium. High silicon gives these rocks their light color. The dominant minerals in these rocks are quartz and orthoclase feldspar. Biotite, amphibole, and plagioclase feldspar may also be present in small quantities.
2. **Mafic rocks** are dark-colored (black or dark green) because they are low in silicon and high in the chemical elements iron, magnesium, and calcium. Mafic rocks are composed of the minerals pyroxene and calcic plagioclase. Ultramafic rocks consist of pyroxene and olivine.
3. **Intermediate rocks** are usually medium to dark brown or gray and are intermediate in silicon, iron, and magnesium content. The dominant minerals are pyroxene and plagioclase, minor biotite, and amphibole.

Question 2. Group igneous rocks by composition in Table 2.

Table 2.

Color	Light/pink	Medium/ gray	Dark/black	Dark/Green, Dense
Composition	**Felsic**	**Intermediate**	**Mafic**	**Ultramafic**
Rock Number				

Part III. Igneous rock identification – EXPLAIN

Question 1. Identify the names of the igneous rocks from your lab using Tables 1, 2, and 3. List the rock number and rock name in Table 4.

Table 3. Igneous rock table

Texture	Composition		
	Felsic	**Intermediate**	**Mafic**
Phaneritic	Granite	Diorite	Gabbro
Aphanitic	Rhyolite	Andesite	Basalt
Porphyritic	Porphyritic Rhyolite	Porphyritic Andesite	Porphyritic Basalt
Vesicular	Pumice		Scoria
Glassy	Obsidian		
Pyroclastic	Volcanic Tuff		

Table 4. Igneous rock activity table

Texture	Composition		
	Felsic	**Intermediate**	**Mafic**
Phaneritic			
Aphanitic			
Porphyritic			
Vesicular			
Glassy			
Pyroclastic			

Part IV. Igneous rocks mineral abundances – ELABORATE 1

Mineral proportions

Figure 2 lists common igneous rocks classified by composition, cooling history (extrusive or intrusive), and mineral abundances. Note the minerals present in each compositional group are the same regardless of cooling history. The dark and light shading of the mineral types reflects how the minerals in the rocks determine the rocks color.

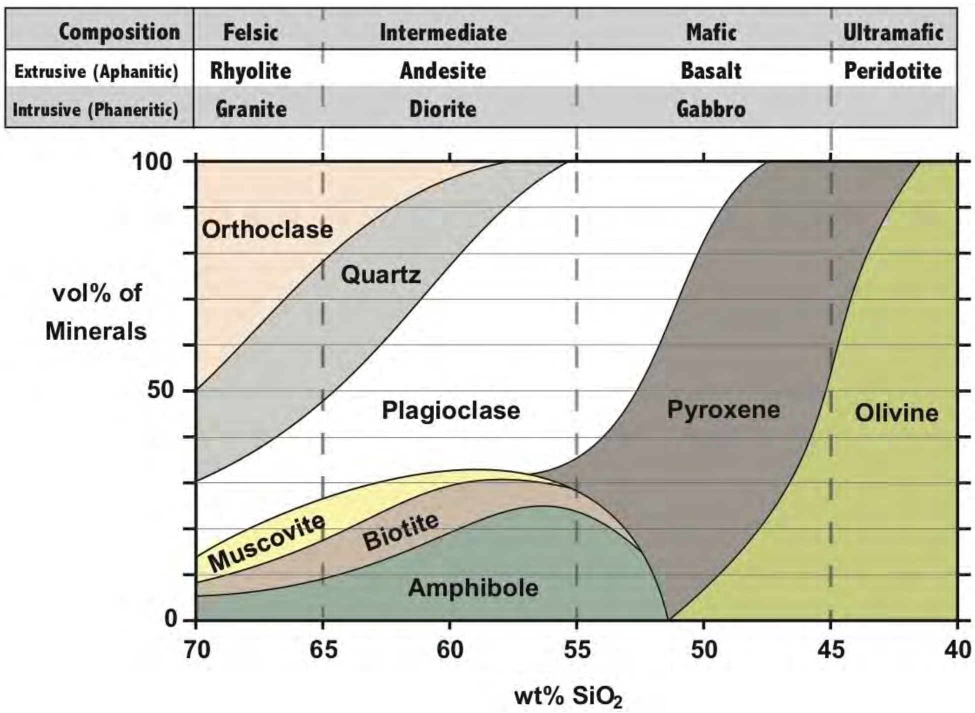


Figure 2. Igneous rock compositions, rock types, and mineral abundances.

Question 1. Use Figure 2 to determine the approximate abundance of minerals in intermediate and mafic igneous rocks. Felsic with 70 percent SiO2 (silicon dioxide) is completed to help you read the chart. List your answers in Table 5.

Table 5.

		Composition		
		Felsic (70% SiO2)	**Intermediate (65% SiO2)**	**Mafic (55% SiO2)**
Volume % of minerals in rock	**Orthoclase**	50		x
	Quartz	20		x
	Plagioclase	15		
	Pyroxene	x	x	x
	Muscovite	5		
	Biotite	5		
	Amphibole	5		
	Olivine	x	x	x

Part V. Igneous rocks and tectonic environments – ELABORATE 2

Tectonic settings and igneous rock formation

Most magmas form at plate boundaries and hotspots due to either (1) pressure release, (2) an increase in temperature, or (3) the addition of volatiles such as water and carbon dioxide gas.

1. As shown in Figure 3, composite volcanoes with **felsic** (rhyolite) and **intermediate** (diorite) magma compositions form above subduction zones, either on ocean-ocean **convergent boundaries** (left) or ocean-continent **convergent boundaries** (right).
2. At **divergent boundaries** (center), magmas with **mafic** (basaltic) compositions form. Above mantle hotspots, shield volcanoes with mafic (basaltic) magmas form.

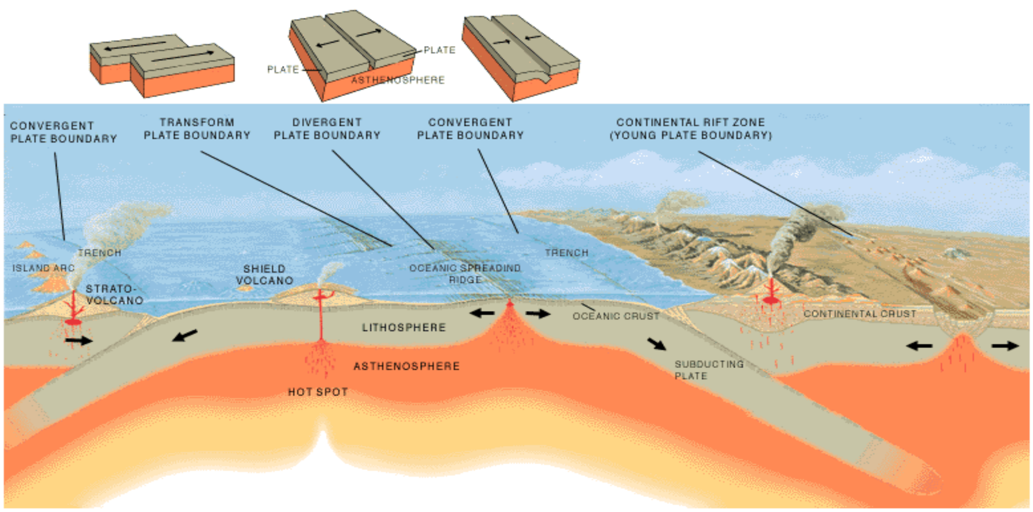


Figure 3. Plate tectonic settings of igneous rock occurrences. From USGS.

Question 1. Use Figure 3 to determine the relationship between tectonic setting and igneous rock composition. Write in each box "YES" (for correct) or "NO" (for incorrect) in Table 6. Also add rock numbers from the images.

Table 6.

Tectonic Setting	Composition		
	Felsic	**Intermediate**	**Mafic**
Convergent Margin			
Divergent Margin			
Hotspot			

Question 2. Open https://www.google.com/maps in your internet browser and click on satellite mode. From your current location, zoom out to find the nearest plate boundary where felsic or intermediate volcanism is occurring. Then find the nearest plate boundary where mafic volcanism is occurring. List your answers in Table 7.

Table 7.

Name your location on the map	
Name the location of nearest plate boundary with felsic or intermediate volcanism (convergent)	
Name the location of nearest plate boundary with mafic volcanism (divergent)	

Part VI. Questions – EVALUATE

Question 1. Describe aphanitic texture.

A. Aphanitic texture is a rock without crystals, which indicates formation from a rapid-cooling lava.
B. Aphanitic texture is a rock with holes or vesicles and indicates bubbles of gas trapped in lava as it cooled.
C. Aphanitic texture is found in extrusive rocks. The crystals in the rock are too small to identify without magnification.
D. Aphanitic texture is found in intrusive rocks. The crystals in the rock are large enough to see without magnification.

Question 2. In what environment do phaneritic (plutonic or intrusive) rocks cool?

A. Above ground.
B. Underground.
C. Under water.

Question 3. Describe how vesicular rocks form.

A. They are made up of a mix of glass shards, fragments of crystals, and small pieces of pre-existing (often aphanitic) igneous rock that welded together.
B. This rock had two rates of cooling with visible crystals cooling slowly underground and the finer ground mass cooling rapidly above ground.
C. They formed from lava that cooled so quickly at the Earth's surface that no crystals had a chance to form.
D. These rocks had hot gas bubbles or holes (vesicles) were trapped in the lava as it cooled.

Question 4. The bear den granite is light in color and has large crystals. What was the tectonic environment of New York about 350 Ma when this rock formed?

A. Convergent plate boundary
B. Divergent plate boundary
C. Transform plate boundary

Question 5. Although it is a felsic rock, why is obsidian typically dark in color?

A. It contains minerals with mafic compositions that give it the dark color.
B. It contains minerals with intermediate compositions that give it the dark color.
C. It is often dark in color due to impurities.

Question 6. Explain why basalt and scoria have the same abundance of minerals.

A. They are both rocks with felsic compositions; however, they cooled in different ways.
B. They are both rocks with mafic compositions; however, they cooled in different ways.
C. One is phaneritic, and one is aphanitic.

Question 7. The Palisades Sill is dark in color and has a mafic composition. What was the tectonic environment of New York about 200 Ma when this rock formed?

A. Convergent plate boundary
B. Divergent plate boundary
C. Transform plate boundary

Question 8. Which rock is phaneritic (intrusive) and has an intermediate composition?

A. Andesite
B. Diorite
C. Scoria
D. Obsidian

Question 9. Which phaneritic (intrusive) rock has about 50 percent orthoclase feldspar and 20 percent quartz?

A. Gabbro
B. Diorite
C. Granite
D. Rhyolite

Question 10. What composition of igneous rocks is the oceanic crust made of?

A. Rhyolite or granite
B. Andesite or diorite
C. Basalt or gabbro
D. Peridotite

Question 11. The Palisades Sill that towers over the Hudson River in New Jersey is made up of mafic igneous rock that intruded the area about 200 million years ago. What type of rock would you find if you were to visit the sill?

A. Basalt
B. Gabbro
C. Diorite
D. Granite

Image sources

Figure 1a. By Beyond My Ken - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=29893514

Figure 1b. Harvey Barrinson, Bronx Zoo_2015 05 24_0141, CC BY-NC-SA 2.0 https://www.flickr.com/photos/hbarrison/18251704089/in/photostream/

Figure 3. This Dynamic Earth [USGS]. (5 May 1999). Retrieved January 7, 2022, from https://pubs.usgs.gov/gip/dynamic/dynamic.html#anchor19309449

5. What do sedimentary rocks tell us about the past?

What were the conditions like when the sedimentary rocks of the Feltville formation were deposited?

Introduction

Any rock at the Earth's surface is being slowly changed by the processes of weathering. This produces new materials called sediments. A sediment consists of loose grains of broken-down rock, shells, or plant debris. Sedimentary rocks form either when sediments are compacted and cemented together, or when dissolved minerals precipitate or solidify from water solutions near Earth's surface. Sedimentary rocks record past environments and past lifeforms in the fossil record. By matching modern environments where a distinct type of sediment is forming today to sedimentary rocks with similar characteristics, we can learn about past environments on Earth.

Purpose

In the following exercises you will learn how to identify and classify common sedimentary rocks based on their textures and properties, determine the depositional histories of common sedimentary rocks, and determine the relationships between sedimentary rock types and past environments.

Learning Objectives

After doing this lab you will be able to:

1. Classify sedimentary rocks based on their characteristics (grain size, grain shape, grain sorting, and composition) and determine their depositional environments.
2. Explain the different environments in which sedimentary rocks form.

Part I. Introduction to sedimentary rocks – ENGAGE

The Newark Basin in New Jersey formed as Pangea broke apart about 200 million years ago. The Feltville formation, a rock unit within the basin, consists of layers of sandstone and red siltstone. It contains fossil evidence of dinosaur tracks, root structures, and fish (Fig. 1).

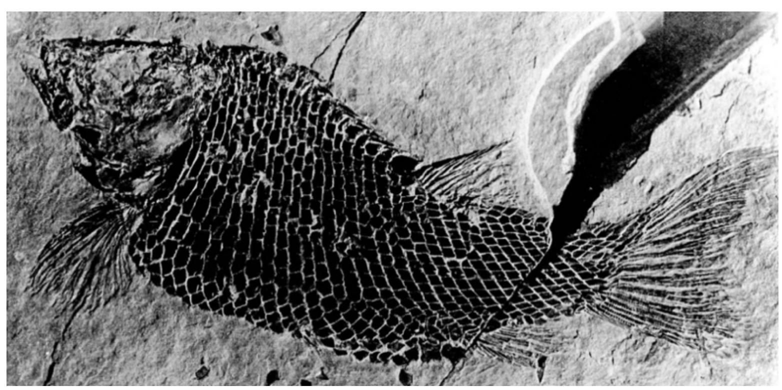


Figure 1. (a) Layers of rock (left; By Lithium6ion) and (b) a common fish species of the Feltville formation (*Semionotus sp.*), Newark Basin (From Olsen, 1988).

Question 1. What were the conditions like when the sedimentary rocks of the Feltville formation were deposited? Use your imagination to write a short geologic history that describes the conditions that led to the deposition of sediments in the Feltville formation.

Part II. Identifying sedimentary rocks – EXPLORE

Materials needed

- 10-12 common sedimentary rocks (or images of rocks; see appendix 2 for rock images)
- Dilute hydrochloric (HCl) acid

Question 1. Warm-up activity. Examine the sedimentary rocks or images provided. Observe if grains exist, the size and shape of the grains, if there are any visible fossils (evidence of life), how the rock looks, etc. In Table 1 list some ways to divide these rocks into groups or categories. Compare your classification scheme to another student's. Add any categories that you had not thought about.

Table 1.

Rock Numbers	Grouping

Question 2. In Table 2, group the rocks based on whether they have clasts (visible grains) or not. Rocks without clasts may have crystalline or cryptocrystalline (glassy) textures.

Table 2.

	Rocks with clasts	Rocks without clasts
Rock Numbers		

Question 3. Use the diagnostic chart (Fig. 2) to identify your images of sedimentary rocks. List these rocks in Table 3. Use Figure 4 to determine the grain size, and use Table 4 to identify the depositional environment in which each rock formed. Once you have filled out your chart, discuss your answers with your instructor (**EXPLAIN**).

Figure 2. Sedimentary rock classification scheme.

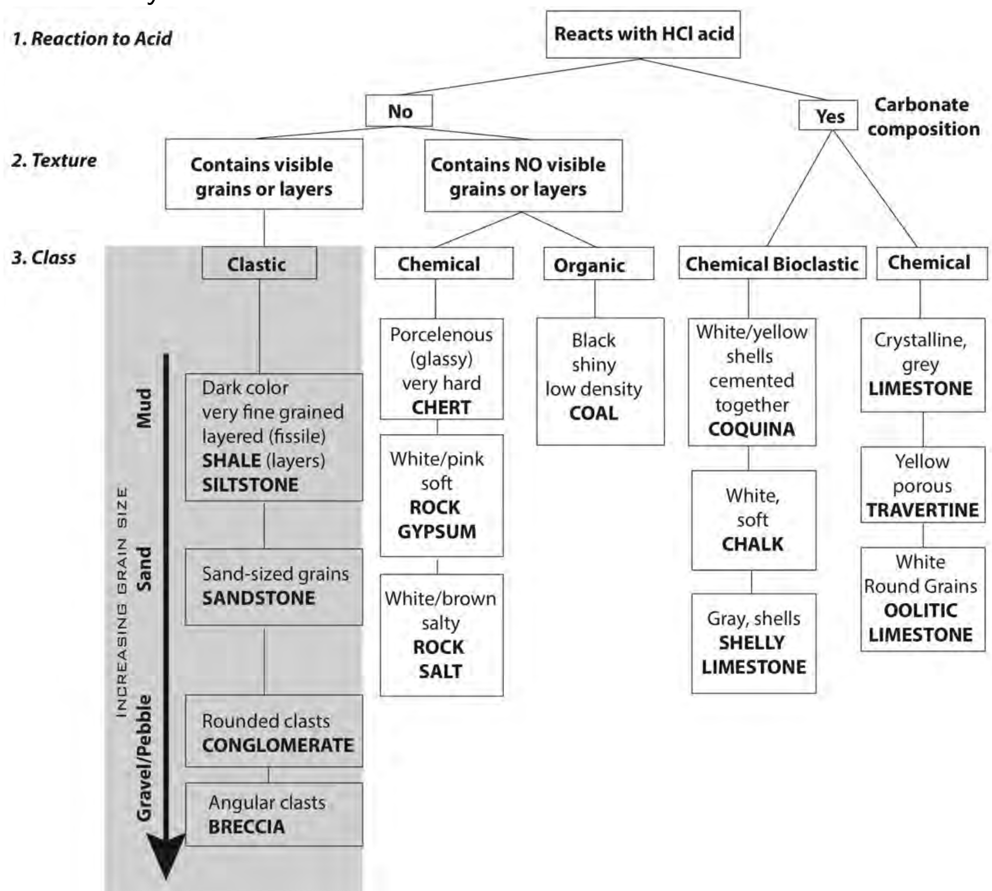


Table 3.

Rock Number	Class: Clastic, Chemical, Chemical biogenic, Organic	Grain size of clastic rocks (pebble, sand, silt, mud)	Rock Name	Past Depositional Environment

How are sediments and sedimentary rocks formed?

Weathering is the process that breaks down rocks, shells, and organic matter at Earth's surface to create materials called sediments. **Physical weathering** mechanically breaks down these natural materials through the abrasive action of streams, ocean waves, wind, ice, or gravity, not changing the composition of the rock. **Chemical weathering** forms sediments by chemical reactions such as dissolving materials to form a solution. New minerals precipitate from these solutions in three ways: (1) directly, (2) through evaporation of the fluid, or (3) when organisms extract the dissolved minerals from water to form casings such as shells or reefs. Rare sediments form from organic material, such as plants or plankton, when organisms die and are buried. Once formed, sediments are commonly transported by water, wind, or ice and deposited at a location where they accumulate over time and are compacted and lithified or hardened into a rock.

Sedimentary rock groups

Sedimentary rocks are classified as either:

1. **Detrital or Clastic**. Made from fragments or clasts of pre-existing materials cemented together.
2. **Chemical**. Formed from minerals precipitating from a water solution directly or by evaporation. Chemical sedimentary rocks are biogenic in origin when organisms assist in extracting and precipitating new minerals from a solution.
3. **Organic**. Formed from organic matter that is buried and hardened into rock.

Formation of detrital or clastic sedimentary rocks

Detrital or clastic sedimentary rocks are the most common type of sedimentary rock. They form by following steps:

1. **Weathering**: breaks down a pre-existing rock into a sediment.
2. **Erosion**: Moving water, wind, or ice pick-up the weathered fragments.
3. **Transportation**: Water (streams or ocean waves), wind, or ice (glaciers) move clasts away from their source rock.
4. **Deposition**: When the transporting water or wind slows or the ice melts, clasts settle out of the transporting medium and accumulate. This typically occurs in a water environment such as the ocean floor.
5. **Compaction**: As sediments accumulate in layers, the weight of the overlying sediment closes spaces between the grains and squeezes out any water.
6. **Lithification or cementation**: Fluids between sediment grains containing dissolved minerals hardens to form a glue that cements the grains together to form a rock (Fig. 3).

Figure 3. Deposition (left), compaction (middle), and cementation (right) leads to lithification of sediments to form a clastic sedimentary rock. From Preuss, P. (2003)

Classification of detrital or clastic sedimentary rocks

Clastic sedimentary rocks are classified and named based on grain size (Fig. 4).

1. **Conglomerate** and **breccia** are sedimentary rocks with gravel- to boulder-sized grains cemented together. If clasts are rounded, the rock is conglomerate. If clasts are angular and jagged, the rock is breccia.
2. **Sandstone** consists of sand-sized grains and feels like sand to touch. It is usually pale yellow to orange in color.
3. **Siltstone** contains silt-sized grains and is dark in color.
4. **Mudstone and shale** contain mud-sized grains. If there are layers along which the rock splits, the rock is called shale. This rock is often dark in color because it contains organic matter.

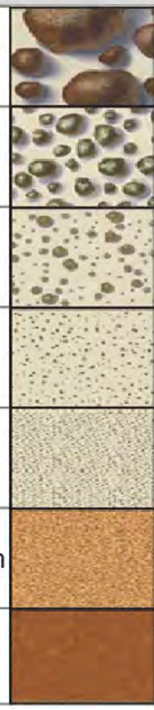
Clast Size (millimeters)		Sediment Name	Rock Name
256 - 4 mm		Gravel	Conglomerate (rounded grains)
4 - 2 mm		Pebbles	Breccia (angular grains)
2 - 0.5 mm		Sand (coarse)	Sandstone
0.5 - 0.25 mm		Sand	
0.25 - 0.06 mm		Sand (fine)	
0.06 - 0.004 mm		Silt	Siltstone
<0.004 mm		Mud	Mudstone Shale (if layered)

Figure 4. A modified Wentworth Scale specifying sizes of sedimentary clasts and their related rock types.

Grain sizes, shapes, and organization

Within a sediment and sedimentary rock, the **grain size, grain shape**, and organization or **sorting** of grains provides information about the history of the grains and the environment in which the sediments were deposited (Fig. 5).

1. **Grain size:** The larger a grain size, the closer the sediment is to the source rock from which it formed. The smaller the grain size, the farther the sediment has traveled from its source.
2. **Grain shape:** The more angular a grain, the less it has been abraded during transportation and the closer it is to the source rock. The more rounded the sediment grain, the farther it has been transported and traveled from its source rock.

3. **Organization or sorting** refers to the degree of uniformity of grain size. A poorly sorted sediment has sediments of all sizes. It forms closer to the source rock and may have been rapidly deposited. A well-sorted sediment, with grains of the same shape and size, was transported farther from its source rock and indicates that it has been worked by wind or water over a long period of time.

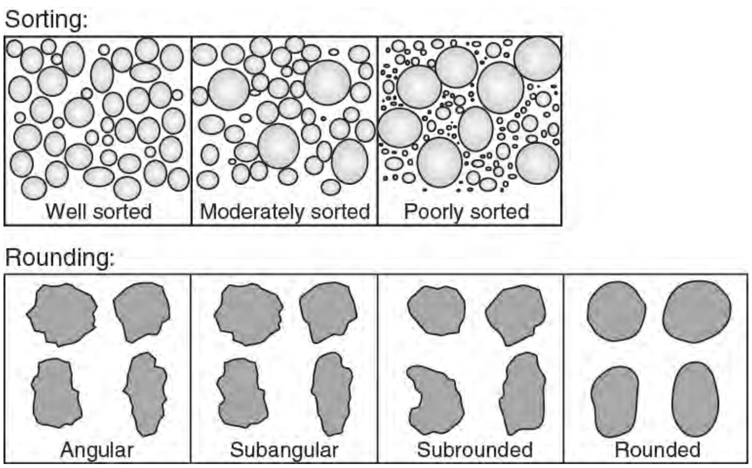


Figure 5. Top: A well-sorted sediment (left) to a poorly sorted sediment (right). Bottom: Angular (left) to rounded grains (right). The more sorted and rounded the grains, the more transportation and abrasion they have experienced (by wind, water, or ice), indicating farther travel by the sediment from its source rock. From McNeill et al. (2017)

Chemical sedimentary rocks
Chemical sedimentary rocks form when solid minerals precipitate from water containing dissolved materials. Environments where this occurs includes hot springs, cave walls, lakes, seas, the ocean floor, and within sedimentary rocks. The composition of chemical sedimentary rocks depends on the materials dissolved in the water from which the rock formed. In some of these rocks the crystals are visible, and in others the rocks have glassy or cryptocrystalline textures.

Chemical sedimentary rocks are identified based on composition:

1. **Rock salt** is composed of halite (table salt) and forms when seawater evaporates. This rock has crystals that are clear to gray in color and taste salty.
2. **Rock gypsum** is composed of gypsum and forms when seawater evaporates. This rock has crystals that are pink to white and are softer than a fingernail.
3. **Limestone** is composed of calcite and forms directly (or indirectly; see biogenic limestone) from seawater. This rock is typically gray and crystalline and will react to acid.
4. **Travertine** is composed of calcite and forms in hot springs. This rock is white to brown, has small holes, and reacts with acid. Stalactites and stalagmites are cave deposits that from calcite-rich groundwater.
5. **Oolite or oolitic limestone** is composed of small round grains of calcite. This rock is white and reacts with acid.
6. **Chert** is composed of silica and hardens from silica gels accumulated on the deep-sea floor. It also forms when silica-rich fluids in sedimentary rock replace materials (including wood, to form petrified wood). This rock may be known as **jasper**. Chert can be gray, white, or red. It has a cryptocrystalline texture and is very hard.
7. **Dolostone** is limestone that had its composition changed by magnesium-rich fluids passing through the rock to form a Mg-carbonate composition. This rock is crystalline, gray to brown, and may react with acid.

Biogenic (chemical) sedimentary rocks
Organisms, such as ones that build shells or reefs, can play a role in precipitating minerals from fluids to form biogenic (chemical) sedimentary rocks. These rocks include:

1. **Biogenic limestone** formed from shells or reefs of calcite-secreting organisms. This rock may contain shells or other shallow marine fossils. It's typically gray and reacts to acid.
2. **Chalk** is composed of tiny micro-organisms made with calcite casings. This rock reacts to acid.
3. **Coquina** is a bioclastic limestone in that it is made of clasts of small shells cemented together. This rock reacts to acid.
4. **Biogenic chert** formed from the casings of silica-secreting microscopic plankton and sponges.

Organic sedimentary rocks
Organic sedimentary rocks are made of the remains of once-living organisms. The main rock in this group is **coal,** which forms from trees that are buried, heated, and transformed into a carbon-rich rock over a long period of time. This rock can look glassy and has a low density (feels light when you pick it up). **Amber**, which is fossilized tree sap, also occurs in this group.

Clastic and chemical sedimentary depositional environments
By matching modern environments in which a distinct type of sediment is forming today to sedimentary rocks with similar characteristics, we can learn about past environments (Table 4).

Table 4. Depositional environments for sedimentary rocks.

Clastic Sedimentary Environments	**Rock Name**
Tallus slope (e.g. landslide) with little transportation of sediment or glacial till	**Breccia**
Streams and riverbeds	**Conglomerate**
Beach or desert sand dunes	**Sandstone**
Lagoons, lakes, deep ocean floor, nearshore tidal flat, or wetlands	**Mudstone, siltstone, or shale**
Chemical Sedimentary Environment	**Rock Name**
Shallow, tropical ocean	**Limestone, biogenic limestone, oolitic limestone, fossiliferous or shelly limestone, chalk, coquina**
Hot springs	**Travertine**
Deep ocean basin	**Chert**
Groundwater replacement	**Chert, jasper, petrified wood**
Caves	**Stalactites/stalagmites**
Evaporated seawater (arid)	**Gypsum, halite**
Organic Sedimentary Environment	**Rock Name**
Trees that are buried and heated	**Coal**

Part III. Interpreting sedimentary rock environments – ELABORATE

Sedimentary rocks form at the Earth's surface and record information about depositional environment at the time and place the rock formed. This makes sedimentary rocks useful tools for interpreting Earth's history. When these rocks contain fossils, we can also learn about past lifeforms.

The Newark Basin, located in New Jersey, consists of sedimentary and volcanic rocks that formed as Pangea broke apart 200 million years ago (Fig 6). In this activity we will focus on the Feltville Formation in the upper layers of the Newark Basin to understand the past environments in our region.

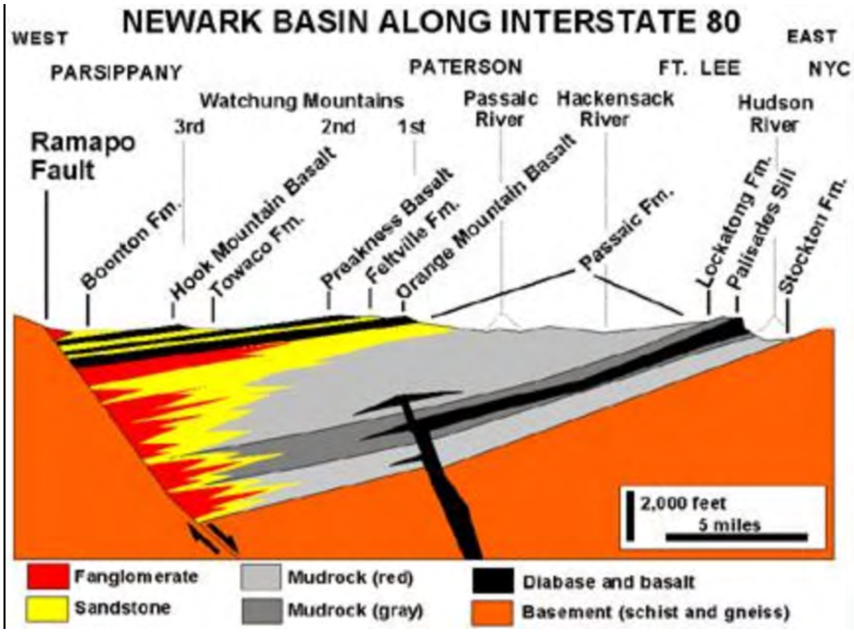


Figure 6. Rock units of the Newark Basin, New Jersey.
From Stoffer, P. (2011)

Step 1. Go to the web links below to learn about the Feltville Formation:

1. https://mrdata.usgs.gov/geology/state/sgmc-unit.php?unit=NJJf%3B2
2. https://en.wikipedia.org/wiki/Feltville_Formation

Question 1. Describe the depositional environment, age, and evidence of fossils (past life) for the Feltville formation.

Depositional environment:	
Age of formation:	
Fossil evidence:	

Question 2. Write a short geologic history that describes the conditions that led to the deposition of sediments for the Feltville formation.

Question 3. Sketch the environment when the sediments that make up the Feltville Formation were being deposited.

Part IV. Questions – EVALUATE

Question 1. What are the three groups of sedimentary rocks?

Question 2. How are clastic or detrital sedimentary rocks classified?

A. By grain size
B. By the composition of the minerals present in the rock
C. By the shape of the rock
D. By the fossils in the rock

Question 3. What is the main way chemical sedimentary rocks are classified?

A. By grain size
B. By the composition of the minerals present in the rock
C. By the shape of the rock
D. By the fossils in the rock

Question 4. Chemical limestone forms when solid minerals precipitate from water containing dissolved materials. Chemical biogenic limestone forms from organisms that secrete calcite to make shells or reefs.

A. True
B. False

Question 5. A sedimentary rock with clasts ranging between 2mm and 0.5 mm is a

A. Breccia
B. Conglomerate
C. Sandstone
D. Shale

Question 6. A sedimentary rock with clasts larger than 2 mm that are angular in shape is a

A. Breccia
B. Conglomerate
C. Sandstone
D. Shale

Question 7. Sedimentary rocks record past environments and past lifeforms in the fossil record. By matching modern environments where a distinct type of sediment is forming today to sedimentary rocks with similar characteristics, we can learn about past environments on Earth. Provide an example of this.

A. Limestone indicates a shallow ocean in a warm climate.
B. Conglomerate indicates a riverbed environment.
C. Sandstone indicates a past beach or desert environment.
D. Shale indicates a past lagoon or lake.
E. All of the above

Question 8. Describe how a sediment's particle size changes as you move away from the source of the sediment.

A. Particle size increases
B. Particle size decreases
C. Particle size stays the same

Question 9. Describe how a sediment's shape changes as you move away from the source of the sediment.

A. Sediment shape becomes more angular
B. Sediment shape becomes more rounded
C. The grain shape stays the same

Question 10. Describe how a sediment's sorting changes as you move away from the source of the sediment.

A. The sediment grains become more sorted
B. The sediment grains become less sorted
C. The sediment sorting does not change.

Question 11. The Newark Basin was deposited by streams that flowed across the eastern part of the United States in the Jurassic period between 199 and 199 million years ago as Pangea was pulling apart and the Atlantic Ocean was opening. Figure 6 shows a cross-section through the basin. Note the sedimentary rock types fanglomerate, sandstone, and mudrock. Considering that particle size decreases as the sediment moves away from the source, what is the general direction of the stream flow in this area during the Jurassic period?

A. North to south B. South to north
C. East to west D. West to east

Image Sources:

Figure 1a. By Lithium6ion - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=17865989

Figure 1b. From Olsen, P. E. (1988). Paleoecology and paleoenvironments of the continental early Mesozoic Newark supergroup of eastern North America. In Manspeizer, W. (ed.). Triassic-Jurassic rifting and the opening of the Atlantic Ocean. Amsterdam: Elsevier, pp. 185-230.

Figure 3. Preuss, P. (2003, April 4). How did the oil get into the rock? How can the oil get out? Retrieved January 7, 2022, from https://www2.lbl.gov/Science-Articles/Archive/ESD-oil-in-the-rock.html

Figure 5. McNeill, L. C., Dugan, B., Petronotis, K. E., and the Expedition 362 Scientist. (2017, October 6). Expedition 362 methods. IODP Publications, Volume 362 expedition reports, Expedition 362 methods. Retrieved January 7, 2022, from http://publications.iodp.org/proceedings/362/102/362_102.html

Figure 6. From Stoffer, P. (2011, December 25). NYC regional geology. Geology Cafe. Retrieved January 7, 2022, from http://geologycafe.com/nyc/mesozoic/newarkbasin.htm

6. How can we read metamorphic rocks?

How did the Manhattan schist form?

Purpose

In the following exercises you will become familiar with textures, compositions, and grades of common metamorphic rocks. You will learn how to identify metamorphic rocks and understand the processes that form them.

Learning Objectives

After doing this lab you will be able to:

1. Explain how parent rocks (protoliths) are changed by metamorphism.
2. Explain the difference between foliated and non-foliated metamorphic rock textures.
3. Explain how metamorphic rock textures can lead to determining the rock's composition, grade, and name.
4.

Materials needed

- 8-10 common metamorphic rocks (see appendix 3 for rock images)

Part I. Introduction to metamorphic rocks – ENGAGE

Figure 1. (a - left) The Manhattan schist from New York City and (b - right) a shale that is the parent rock or protolith for the schist. Figure 1a. by James St. John - Mica schist, CC BY 2.0. Figure 1b. by Pollinator, CC BY-SA 3.0.

Question 1. The Manhattan schist (Fig. 1a) was originally a shale that formed on the seafloor (Fig. 1b). The rock shows a banded texture and contains minerals such as red garnet and shiny mica. Propose how the schist could have formed in a sequence of steps?

Stage 1	**Stage 2**	**Stage 3**	**Stage 4**
Mud on seafloor that lithified into a shale.			Banded schist with garnet and mica.

Part II. Textures in metamorphic rocks – EXPLORE

A metamorphic rock is a rock that has been changed in a solid state (*meta* = change, *morph* = form). The original parent rock, or protolith, of a metamorphic rock can be sedimentary, igneous, and even metamorphic rock. Metamorphic rocks change by growing new minerals and/or forming new textures when exposed to agents such as heat, pressure, hot fluids, and tectonic stress. These conditions happen inside the Earth where there is active tectonism.

Textures and Minerals

Rocks that undergo metamorphism form both new textures and new minerals (though their composition usually does not change) reflective of the metamorphic conditions they formed in. Energy sourced from heating and deformation during metamorphism enable minerals to change shape and re-crystallize, and it also rearranges elements so that new minerals can grow.

Since each mineral has a limited range of environmental conditions in which it can exist (mineral stability), new minerals that grow in a metamorphic rock are indicative of the pressures and temperatures these rocks experienced inside the Earth. Thus we can directly determine the degree to which the rocks were changed by looking at the minerals present in a metamorphic rock.

Metamorphic Rock Textures

Metamorphism creates either foliated or non-foliated textures in rocks. Foliation is a layered or banded appearance due to the alignment of platy (flat) minerals such as mica (e.g., rocks slate, phyllite, schist), or due to compositional layering (e.g., gneiss). Foliated rocks have experienced differential stress (Fig. 2), or greater stress in one direction, causing bands to form perpendicular to the stress direction.

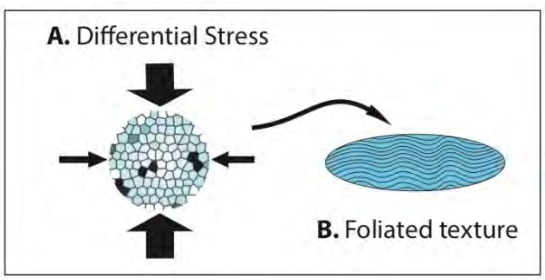


Figure 2. Differentiated stress leads to the development of foliation.

Question 1. In Table 1, group your assigned metamorphic rocks by foliated or non-foliated textures.

Table 1.

Texture	Foliated	Non-foliated
Rock Numbers		

Part III. Identifying common metamorphic rocks – EXPLAIN

Question 1. Use the diagnostic chart (Fig. 3) and Table 3 and 4 to identify the names and grades of the metamorphic rocks from your group of rocks. Write your answers in Table 2. Then use Table 5 to determine the protolith of each rock. When completed review the answers with your instructor.

Figure 3. Diagnostic chart for identifying and naming metamorphic rocks based on texture and composition.

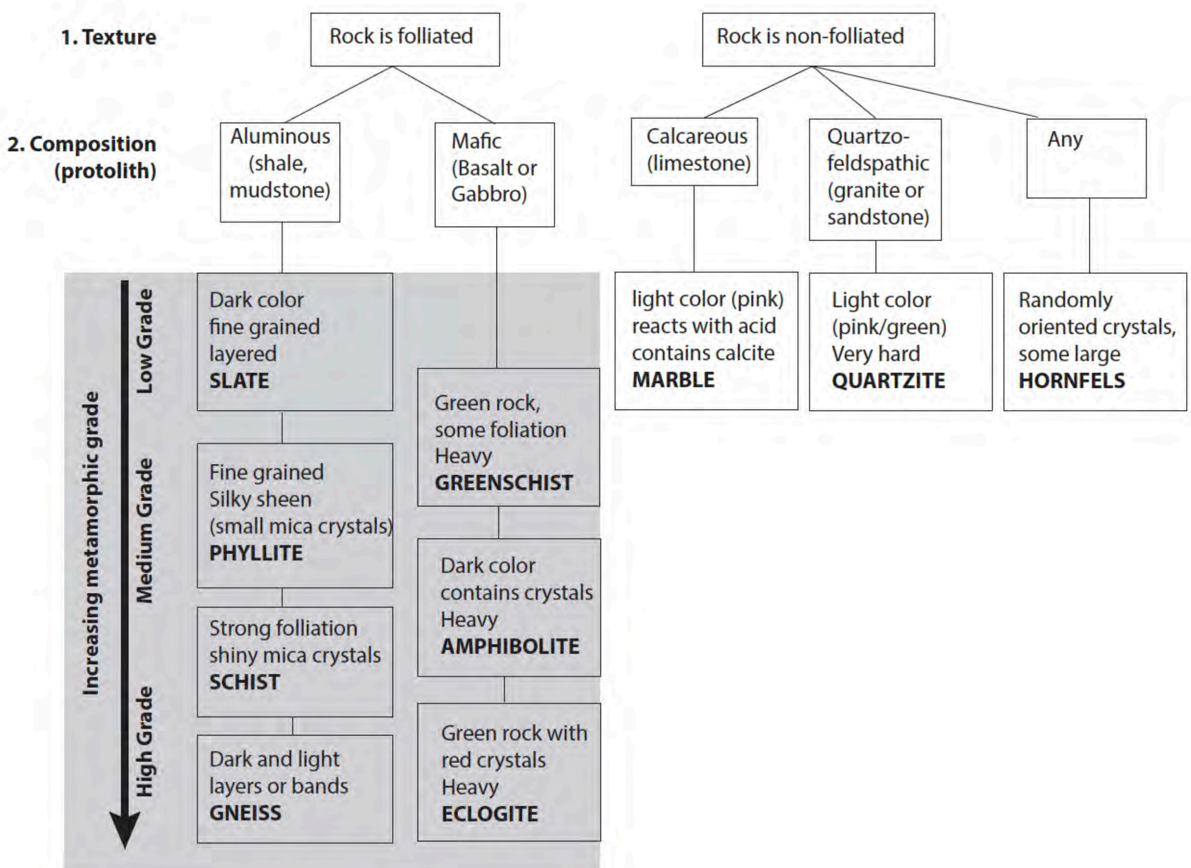


Table 2.

Rock No.	**Texture:** Foliated or Non-Foliated	**Rock Name**	**Protolith:** Mudstone, Limestone, Sandstone, Basalt, Coal	**Grade:** Low, Med, Med-high, High
1				
2				
3				
4				
5				
6				
7				
8				

Foliated Metamorphic Rocks

Foliated metamorphic rocks are classified based on composition and texture. Common rocks are listed in Table 3 in order of increasing exposure to heat and pressure, or metamorphic grade.

Table 3. Common foliated metamorphic rocks.

Slate	A very fine-grained metamorphic rock with thin layers (called slaty cleavage). This rock forms from a sedimentary mudstone or shale.
Phyllite	Tiny crystals of the mineral mica help develop fine layers and a greasy sheen. Phyllite forms from mudstone or shale.
Schist	Visible flakes of the mineral mica form banding known as schistosity. Mica causes these rocks to have a glittery appearance. Schists originate from a parent rock that is a mudstone or shale.
Gneiss	Gneiss rocks have dark and light stripes representing compositional layers or gneissic banding. These rocks form at high enough temperatures and pressures that mica is no longer a stable mineral. The protolith of a gneiss can be a mudstone, shale, or igneous rock.
Migmatites	Migmatites form on the boundary of where metamorphic rocks are heated enough that they transform to igneous rocks. Dark bands in these rocks have remained solid, while light bands, containing felsic minerals with lower melting temperatures, show evidence of melting and can have wavy bands.
Mylonite	Forming in fault zones, or cracks in the earth, where the rock is pulverized and recrystallized as small intergrown grains. Mylonite can form from any protolith.
Amphibolite	This is a dark (almost black) rock containing an abundance of the mineral amphibole. The protoliths of amphibolite are mafic rocks (basalt and gabbro).
Greenschist	Containing the green mineral chlorite and forming a green rock, greenschists form at lower pressures and temperatures or grades than amphibolite. The protoliths of greenschist are mafic rocks (basalt and gabbro).
Eclogite	These rocks form at very high pressures and temperature and contain bright green pyroxene and red garnet. The protoliths of eclogites are mafic rocks (basalt and gabbro).

Non-Foliated Metamorphic Rocks

Non-foliated rocks do not show layering since they tend to either have blocky crystals that do not deform readily when stressed, or to contain only one type of mineral (e.g., marble is made up of calcite) (Table 4).

Table 4. Common non-foliated metamorphic rocks.

Marble	The protolith is the calcite-rich sedimentary rock limestone. Metamorphism causes fossils, shells, and grains to form a crystalline rock with equant crystals. Marble is often white but can be almost any color.
Quartzite	The protolith is the quartz-rich sedimentary rock sandstone. Quartzite is crystalline, can appear to be glassy, and is very hard. Its color can be pink, maroon, white, gray, or green.
Hornfels	This rock is changed only by heating and is made up of equant crystals with a random orientation. Since hornfels can have any protolith, the color and mineral make up of these rocks is variable.

Compositional Groups of Metamorphic Rocks

The composition of the parent rock or protolith determines the type of rock that will form during metamorphism. Rock compositions, corresponding protoliths, and metamorphic rock equivalents are listed in Table 5.

Table 5. Rock compositions, protoliths, descriptions, and metamorphic rock names.

Composition	Protolith	Description	Rock names
Aluminous	Mudstone or siltstone (sedimentary)	Foliated, fine to coarse grained, contains mica (shiny)	Slate, phyllite, schist, gneiss
Calcareous	Limestone (sedimentary)	Non-foliated, light color, reacts with HI acid, contains calcite	Marble
Mafic	Basalt, gabbro (igneous)	Foliated or non-foliated, dark in color Foliated or non-foliated, green matrix and red garnet Foliated or non-foliated, green	Amphibolite Eclogite Greenschist
Quartzo-Feldspathic	Granite (igneous), sandstone (sedimentary)	Foliated and non-foliated, light colored (felsic), very hard	Granite gneiss, Quartzite
Organic	Coal, Peat (sedimentary)	Non-foliated, black, shiny, low density	Anthracite coal

Metamorphic Grade

The extent to which a rock is changed during metamorphism will determine its metamorphic grade. Rocks that are carried to greater depths while being squeezed and heated, such as in a subduction zone or beneath a mountain range, will have a higher metamorphic grade than those that are transported to shallower depths and have not been changed as much. Figure 4 describes the approximate pressures and temperatures of formation of low, intermediate, and high-grade metamorphic rocks.

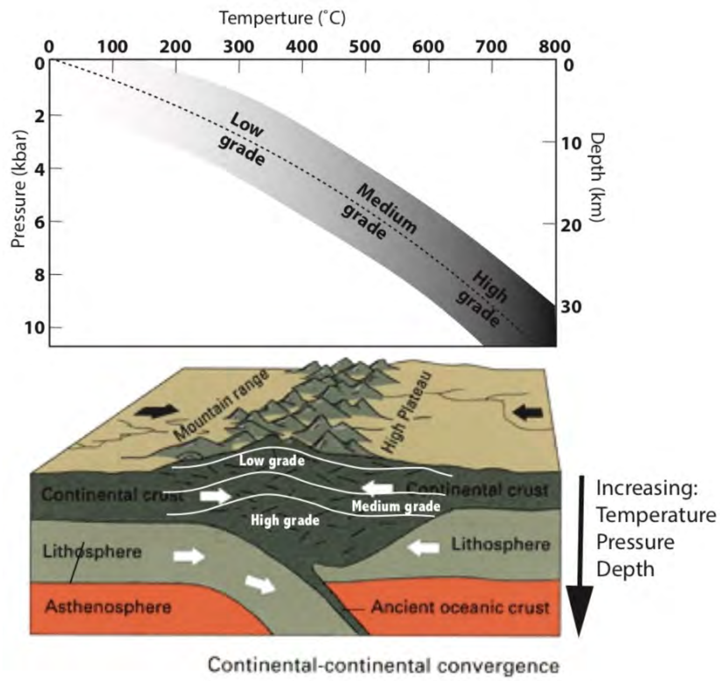


Figure 4. Metamorphic grade increases with increasing pressure, temperature, and depth.
Bottom modified from USGS.

Part IV. Interpreting the metamorphic and tectonic history of New York City – ELABORATE

The Manhattan schist, Fordham gneiss and Inwood marble make up the basement rocks of New York City. In this activity we will interpret the geological history of New York City based on these metamorphic rocks.

Question 1. Use Table 6: What agents were at work to change these rocks to metamorphic rocks?

A. Heat or temperature
B. Pressure
C. Tectonic stress
D. Hot fluid

Question 2. Use Table 7: What type of metamorphism was at work to form these rocks?

A. Regional
B. Thermal or contact
C. Dynamic
D. Hydrothermal

Question 3. Use Table 5.What is the protolith for the following rocks?

Protolith of the Manhattan schist: Protolith of the Fordham gneiss: Protolith of the Inwood marble:

Question 4. Drawing from what you learned in the Sedimentary Rock Lab, what was the depositional environment that formed the protolith of the Inwood marble? What does this tell you about the climate conditions of New York when this rock formed?

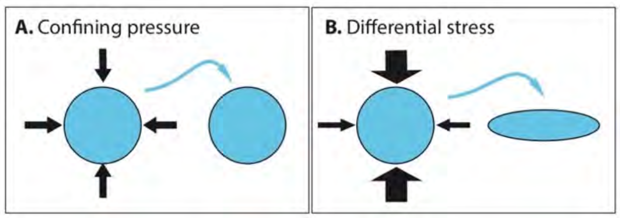
Question 5. Drawing from what you learned in the Sedimentary Rock Lab, what was the depositional environment for the protoliths of the Manhattan schist and Fordham gneiss, which formed offshore? What does this tell you about the environment of New York when this rock formed?

Question 6. Consider the metamorphic grade and foliated texture of the Manhattan schist and Fordham gneiss. What does this tell you about the tectonic setting of New York when these rocks formed?

Agents that change rocks into metamorphic rocks

Metamorphic rocks form inside the Earth where rocks are changed in the solid state. Most metamorphic rocks are changed during deep burial inside the Earth at depths where high temperatures and pressures heat and squeeze rocks and transform their textures and minerals into new ones. For the rocks not to melt (and form igneous rocks), temperatures in the crust are typically between 200 and 900°C. The agents that change rocks are described below in Table 6.

Table 6. Agents that cause metamorphism in rocks.

Temperature or Heat	The sources of heat that change rocks include: (1) the geothermal gradient, which represents an increase in temperature and pressure with depth inside the earth (about 25°C per kilometer); the deeper the rocks are buried, the more they will be heated. (2) coming into **contact** with a hot magma above or below ground.
Pressure	When rocks are buried deep inside the Earth, the overlying pressure or confining pressure squeezes the rock so much as to change them (Fig. 5A). This happens on a regional or large scale where tectonic plates collide to form mountain ranges. Under these conditions rocks commonly experience stress, known as **differential stress**, that is greater in one direction (Fig. 5B), and develop banded or foliated textures as a result.  **Figure 5.** Rocks are changed under confining pressure (A) and differential stress (B).
Tectonic Stress	Along fault zones, or cracks in the Earth, the rocks are under strain due to tectonic stress. Within the fault, frictional forces cause the rock to be heated, leading to the formation of new rock textures. This can happen at shallow depths where rocks deform in a brittle way and breccia forms, and deep enough that rocks deform in a plastic or ductile way and a fine-grained (mylonite) re-crystallized texture forms.
Hot Fluids	Hydrothermal or hot fluids can chemically alter a rock by dissolving compounds or ions in minerals within the rock and causing chemical reactions. Some chemicals are removed and transported out of the rock by hot fluid, while other compounds or ions may be added to the rock. This leads to changes in the composition of the rock. The movement of hot fluids through rocks is one of the only ways metamorphism changes a rocks composition. During metamorphism, rock compositions usually remain the same; only texture and mineralogy are changed.

Types of Metamorphism

Metamorphic rocks can form in several environments, each of which causes different types of metamorphism (Table 7).

Table 7. Types of metamorphism.

<table>
<tr>
<td>Regional Metamorphism</td>
<td>This is the most common type of metamorphism and happens when a rock is carried downward into the crust or mantle when tectonic plates collide. The rocks are changed on a large scale when expanses of Earth's plate boundaries bend and buckle at these collision zones to form mountains. The rocks later emerge during erosion and uplift that expose the cores of former mountains. Pressure (differential stress) and temperature are the agents that change the rocks in this setting (Fig. 6a). These rocks tend to show foliated textures.

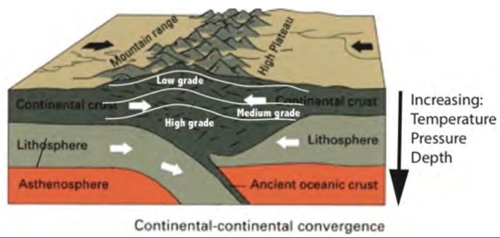


Figure 6a. Conditions for the formation of regional metamorphic rocks. Modified from USGS.</td>
</tr>
<tr>
<td>Thermal or contact metamorphism</td>
<td>Rocks are changed by a baking effect when molten magma is in contact with a solid rock (Fig. 5b). The rock does not melt but is heated and changed. Temperature is the agent of change for these rocks. Rocks forming in this setting are called hornfels.

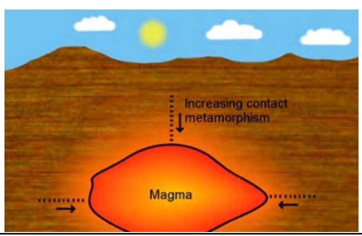


Figure 6b. Conditions for the formation of contact metamorphic rocks. By Jasmin Ros, CC BY-SA 3.0.</td>
</tr>
<tr>
<td>Dynamic metamorphism</td>
<td>These rocks form along fault zones where there is tremendous localized shear stress. Rocks forming within these fault planes are changed by pressure and temperature largely produced by friction (Fig. 6c).

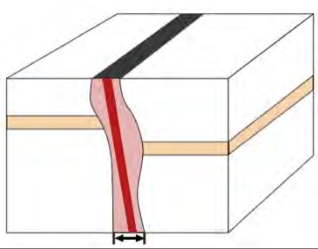


Figure 6c. Conditions for the formation of dynamic metamorphic rocks in fault zones (colored red and black). By Shloscar, CC BY-SA 4.0</td>
</tr>
<tr>
<td>Hydrothermal metamorphism</td>
<td>Rocks are changed when hot fluids percolate through them and alter their chemical composition (also known as metasomatism). This commonly happens on the seafloor where hot magmas lie beneath the surface at divergent plate boundaries. Ocean water heated by the magma travels into cracks in the basaltic crust and alters its composition (Fig. 6d).

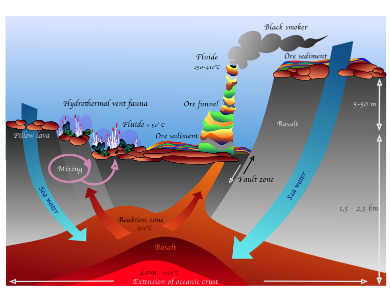


Figure 6d. Conditions for the formation of hydrothermal metamorphic rocks on the seafloor. By Hannes Grobe/AWI, CC BY-SA 4.0</td>
</tr>
</table>

Part V. Questions – EVALUATE

Question 1. What two agents change rocks during regional metamorphism?

A. Tectonic stress and hot fluids.
B. Tectonic stress and temperature.
C. Pressure and tectonic stress.
D. Pressure and temperature.

Question 2. During metamorphism, how does differential stress lead to foliation texture?

A. Hot fluids lead to the layering and alignment of minerals in a metamorphic rock.
B. A rock sitting next to a magma body leads to layering and alignment of minerals in a metamorphic rock.
C. Equal pressure placed on the rock in all four directions leads to layering and alignment of minerals in a metamorphic rock.
D. Greater pressure placed on the rock in two out of four directions leads to layering and alignment of minerals in a metamorphic rock.

Question 3. How does foliation change the appearance of a metamorphic rock?

A. Hot fluids passing through the rock remove minerals and form new ones.
B. It gives the rock a layered or banded appearance.
C. It changes the minerals in the rock.
D. It makes the rock look flat.

Question 4. What type of metamorphism creates foliated rock textures?

A. Burial
B. Hydrothermal
C. Contact or thermal
D. Regional

Question 5. What is the difference between low and high metamorphic grade?

A. Low-grade metamorphic rocks form at high pressures and high temperatures. High-grade metamorphic rocks form at low pressures and low temperatures.
B. Low-grade metamorphic rocks form at low pressures and low temperatures. High-grade metamorphic rocks form at high pressures and high temperatures.
C. Low-grade and high-grade metamorphic rocks form in the same pressure and temperature conditions.

Question 6. What types of metamorphic rocks form from the following protoliths?

A. Basalt:
B. Mudstone:
C. Limestone:

Question 7. How does contact (thermal) metamorphism form metamorphic rocks?

A. By melting rocks in the crust to form magma.
B. By heating rocks without melting them to form new minerals.
C. By melting only parts of rocks to form new minerals.
D. By applying great pressure in the roots of mountains.

Question 8. When the bedrock of New York City formed millions of years ago, what was the region like?

A. It was covered by warm, tropical, shallow oceans.
B. It was underwater with an ocean floor covered in muddy sediments.
C. It was near a convergent plate boundary. Oceanic crust and sediments were being subducted under high pressures and temperatures.
D. All of the above.

Question 9. Having learned more about metamorphic rocks by completing this lab, further discuss the steps that led to the formation of the Manhattan schist (Fig. 1).

Stage 1	**Stage 2**	**Stage 3**	**Stage 4**
Mud on seafloor that lithified into a shale.			Banded schist with garnet and mica.

Image sources

Figure 1a. By James St. John - Mica schist (Manhattan Schist, late Neoproterozoic; Manhattan Island, New York City, New York State, USA), CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=84543746

Figure 1b. By Pollinator at English Wikipedia - Own work by the original uploader, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=42523870

Figure 4. This Dynamic Earth [USGS]. (5 May 1999). Retrieved January 7, 2022, from https://pubs.usgs.gov/gip/dynamic/dynamic.html#anchor19309449

Figure 6a. This Dynamic Earth [USGS]. (5 May 1999). Retrieved January 7, 2022, from https://pubs.usgs.gov/gip/dynamic/dynamic.html#anchor19309449

Figure 6b. By Jasmin Ros - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=28419444

Figure 6c. modified from By Shloscar - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=96271645

Figure 6d. From Hannes Grobe/AWI - Own work (redrawn and modified from a graf in a booklet of BGR: Zu Wasser die Erde erforschen, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=44783414

7. How do scientists measure earthquakes?

Where and how often do earthquakes occur?

Purpose

The purpose of this lab is to become familiar with what an earthquake is, what causes earthquakes to occur, the types of waves generated by earthquakes, and how the waves are measured and used to locate an earthquake epicenter. In addition, earthquake probability and hazard and recent earthquake occurrences are explored.

Learning Objectives

After doing this lab you will be able to:

5. Explain how earthquakes occur.
6. List the types of waves generated during an earthquake.
7. Explain how to measure the distance to the epicenter of an earthquake using a seismogram.
8. Explain how seismic wave amplitude relates to earthquake size and proximity.
9. Explain how the probability of an earthquake relates to the recurrence of earthquakes over time and informs the development of earthquake hazard maps.
10. Explain that earthquakes are happening all the time and are monitored with seismic networks.

Materials needed

- Draftsman compass

Part I. Where and how often do earthquakes occur? – ENGAGE

Step 1. Go to the IRIS Seismic Monitor website http://ds.iris.edu/seismon/

Question 1. What do the circles on the map represent? Why are some small and some larger? How were they measured?

Introduction to Earthquakes

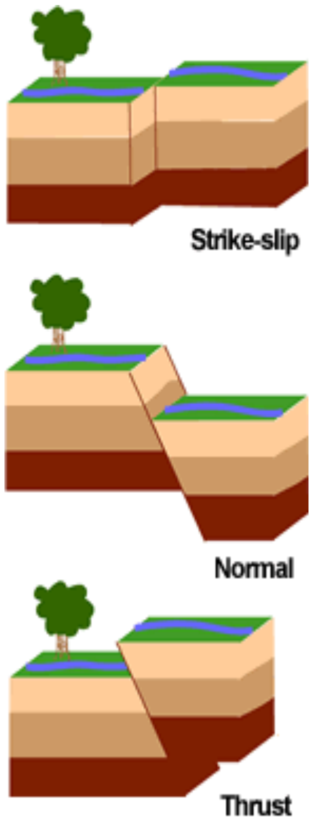


Figure 1. Types of faults along which earthquakes are generated. From USGS.

An **earthquake** is the sudden slip on a fault and the ground shaking and radiated seismic energy caused by the slip. Movement can also be generated by volcanic or magmatic activity or other sudden stress changes in the Earth. A **fault** is a fracture surface between two large regions of rock along which the rock masses have moved relative to one another (Fig. 1). **Strain** in the rocks, caused by tectonic forces near plate boundaries, ultimately causes movement along faults and earthquakes.

In a fault zone, as the strain in the rocks gradually builds up over time, the rock blocks are bent on either side of the fault and undergo **elastic deformation**, much like a stretched rubber band. Eventually, the tectonic forces overcome the shear strength of the rock (the force that is needed to break the rock when acted upon in two opposite directions). The rock then breaks, or undergoes **brittle deformation**, along the fault plane and can slip for some distance. The release of the strain causes the rock to unbend or undergo elastic deformation, much like releasing a stretched rubber band. The bending and subsequent unbending of the crust after slip along the fault called **elastic rebound**.

Blocks of rock do not continuously slip along faults due to friction. **Friction** is the resistance that one surface encounters when moving over another. Faults become locked and don't move for long periods. This allows for significant strain to build up leading to rupture --an earthquake.

Step 2. Watch this video titled "Elastic Rebound Theory." https://www.youtube.com/watch?v=nFv2eaZiR40 and match the questions to the answer options on the following page.

Question 2. What happens to rocks prior to an earthquake? (Hint: Do they undergo elastic deformation or brittle deformation?) Answer:________

Question 3. What happens to rocks during an earthquake? (Hint: Do they undergo elastic deformation or brittle deformation?) Answer:________

Question 4. During an earthquake, at what point is energy released? Answer:________

Question 5. When an earthquake occurs, what is the effect of the energy release? Answer:________

Answer Options

A. In a fault zone, strain in the rocks on each side of the fault builds up over time, and the blocks of rock are bent and undergo elastic deformation.
B. Due to tectonic stress, the strain in the rocks along the fault becomes too great, and the shear strength is overcome. The rocks break or undergo brittle deformation and slip occurs.
C. Energy is released when the rocks along the fault break or undergo brittle deformation. The release of strain causes the rock to undergo elastic rebound return to their undeformed state.
D. The generation of seismic waves and ground shaking.

Part II. Introduction to seismic waves – EXPLORE

When an earthquake occurs, the energy spreads out as seismic waves from the **focus**. The **epicenter** is the land surface above the focus. Earthquakes produce several kinds of seismic waves known as body waves (S- and P-waves) and surface waves. Each kind of wave causes a different kind of motion in the rock as it passes by, and each kind of wave travels through rocks at different speeds. The different types of seismic waves arrive at a distant point on Earth at different times. When each kind of wave arrives depends on its relative speed and its path through Earth. (Fig. 2.)

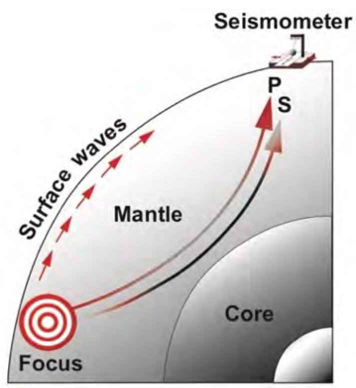


Figure 2. Earthquakes produce body waves (S- and P-waves) and surface waves.

Primary waves (P-waves) are a seismic wave that involves particle motion (compression and expansion) in the same direction the wave is traveling. Away from the focus, these waves are the first to reach a location. They move through solid rock at a speed of about five kilometers per second.

Secondary waves (S-waves) are a seismic wave produced by a shearing motion that involves vibration perpendicular to the direction in which the wave is traveling. These waves arrive after P-waves. They move through rock at a speed of about three kilometers per second.

Surface waves travel along Earth's surface and are the last to arrive at a location. They travel slower than S-waves. They can create an up-and-down rolling motion of the ground, much like waves on the surface of water. They also shake the ground sideways. Surface waves cause the most movement at Earth's surface and are the most damaging to structures.

A seismometer (also known as a seismograph) works on the principle of inertia, which is the tendency for a mass at rest to remain at rest, to record the motions of the ground during an earthquake. These instruments are attached to the Earth and record the ground motion at that location.

A seismogram is a record of earthquake waves. Figure 3 shows a hypothetical seismogram of a single earthquake. Note the separation of P-waves and S-waves on the seismogram. Because the different kinds of waves travel at different speeds, the separation of arrival times between wave types (P-, S-, surface) will increase as the distance from the epicenter increases. Travel-time curves show this relationship (Fig. 4).

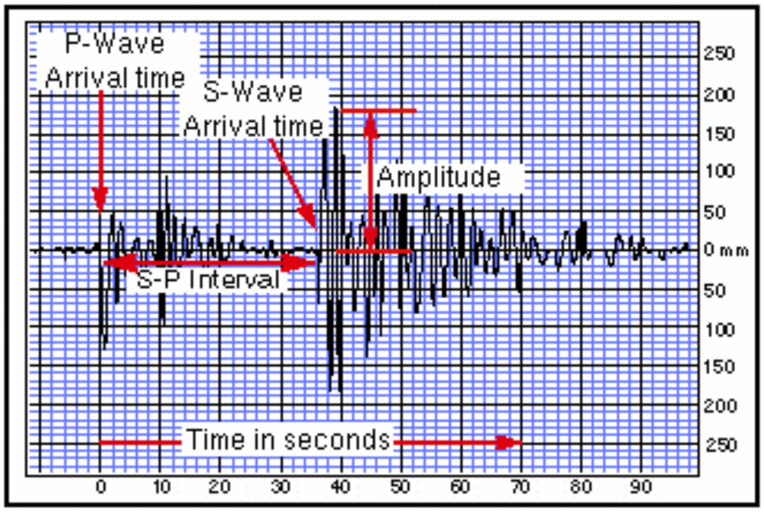


Figure 3. A seismogram showing the arrival time of the P- and S-waves, the S-P interval, and the amplitude or height of the waves. From Virtual Courseware for Earth and Environmental Sciences (2002).

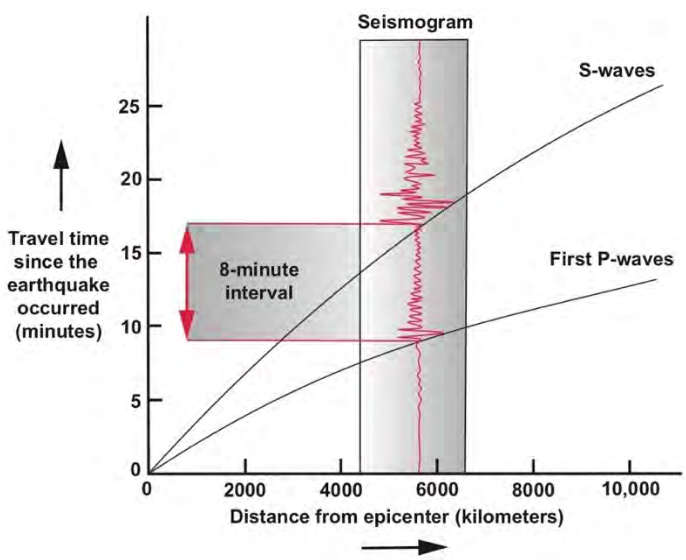


Figure 4. The travel-time graph shows the data from an earthquake and shows the relationship between distance from the epicenter and the difference in arrival times for P- and S- waves.

Step 1. Following the link below, watch the first two minutes of a video about earthquakes to learn about earthquake waves and measuring earthquakes. Then answer the following questions.
https://www.youtube.com/watch?v=FjXb97qR5C8

Question 1. What types of waves are generated during an earthquake?

A. Primary or P-waves
B. Secondary or S-waves
C. Surface waves
D. All of the above

Question 2. What instrument do you use to detect and record the arrival times of earthquake waves?

A. Seismogram
B. Seismometer or seismograph
C. Richtergram
D. Shake map

Part III. Analyzing seismic data and locating an epicenter – EXPLAIN

In order to locate the epicenter of an earthquake you will need to examine the seismograms as recorded by three different seismic stations. On each of these seismograms you will have to calculate the S-wave minus P-wave time interval (in seconds). The S-P time interval will then be used to determine the distance the waves have traveled from the origin to that station.

Step 1. Examine the data shown in the three seismograms in Figure 5, which show a record of the seismic waves detected during an earthquake. The x-axis (horizontal axis) on the graph shows the time in seconds. The y-axis (vertical axis) shows the amplitude or height of each wave.

Question 1. Which seismogram shows the greatest amplitude (wave height)?

A. Eureka, California
B. Elko, Nevada
C. Las Vegas, Nevada

Question 2. Based on the amplitude of the S-wave on the seismogram, which seismograph station is probably closest to the earthquake epicenter?

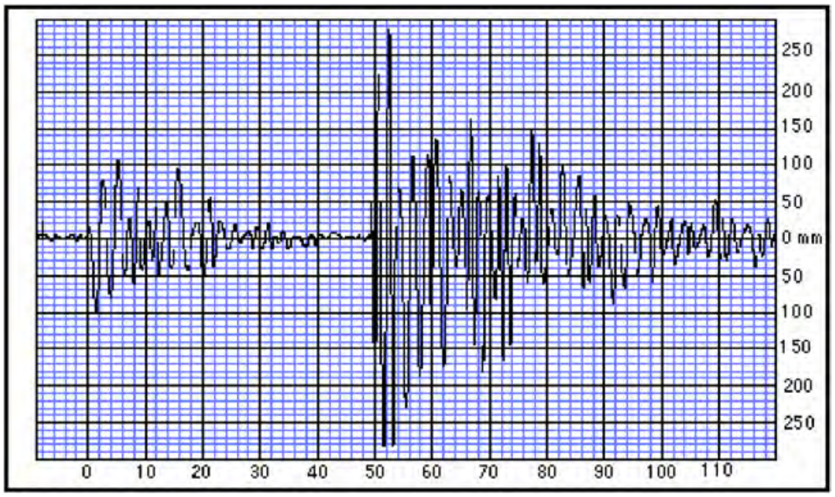
A. Eureka, California
B. Elko, Nevada
C. Las Vegas, Nevada

Step 2. On Figure 5, label the arrival of the primary waves (P-waves) and the secondary waves (S-waves) for each seismogram. Refer to Fig. 3 to inform your answer.

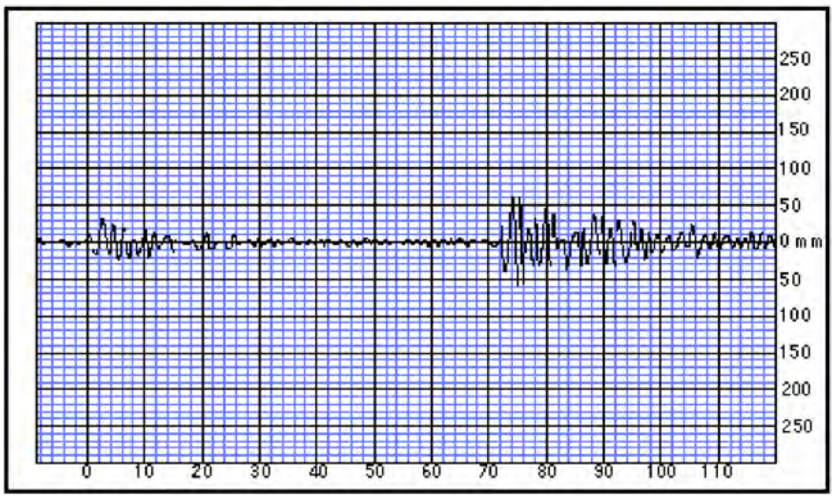
Question 3. Fill Table 1 to record the arrival time of the P-wave, S-wave, and how much time separates the arrival of the P and S waves (S-P).

Table 1.

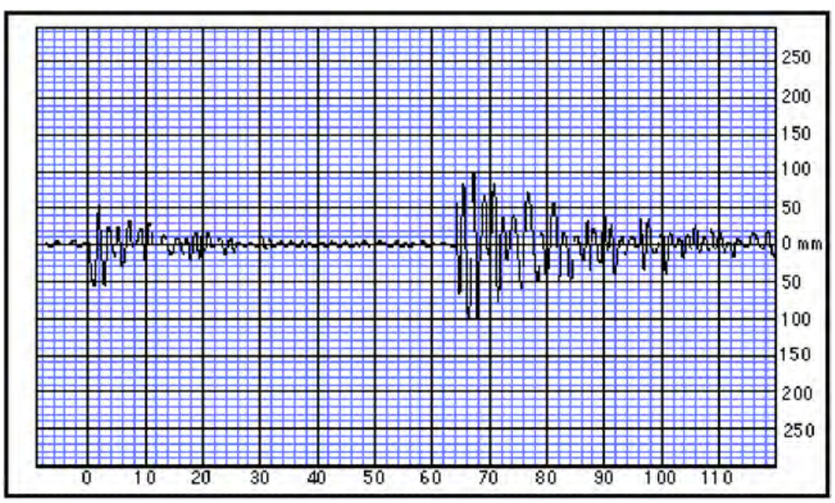
Location	P-wave arrival time (seconds)	S-wave arrival time (seconds)	S-P wave time difference (seconds)	Distance from epicenter (kilometers)	S-wave amplitude (millimeters)
Eureka, CA					
Elko, NV					
Las Vegas, NV					



Eureka, CA Seismic Station (seconds)



Elko, NV Seismic Station (seconds)



Las Vegas, NV Seismic Station (seconds)

Figure 5. Three seismic stations recording P-wave and S-wave travel times and wave amplitudes for an earthquake. From Virtual Courseware for Earth and Environmental Sciences (2002).

Determining the earthquake distance from the epicenter

You can determine the distance from each seismic recording station to the earthquake's epicenter using the known times of travel of the S- and P-waves.

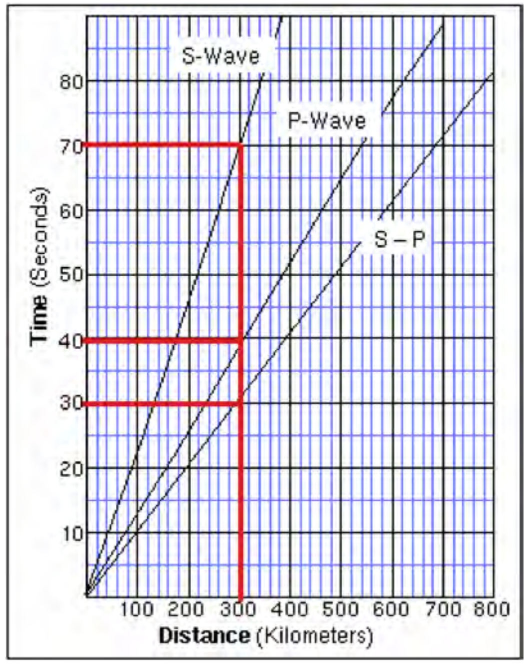


Figure 6 (right) shows seismic wave travel times. There are three lines on the graph:

1. The upper line shows S-wave travel-time graphed versus distance.
2. The center line shows P-wave travel time versus distance,
3. The lower line (S-P) subtracts the individual S- and P- lines to show the difference in S minus P travel times.

For the rest of this exercise you won't be needing the individual S and P lines, only the S-P line which is expanded in Figure 7.

Figure 6 (above). Seismic travel times. Note that it takes an S-wave about 70 seconds, a P-wave 40 seconds, and an S-P interval 30 seconds (or 70 minus 40 seconds) to travel 300 kilometers (top). Adapted from Virtual Courseware for Earth and Environmental Sciences (2002).

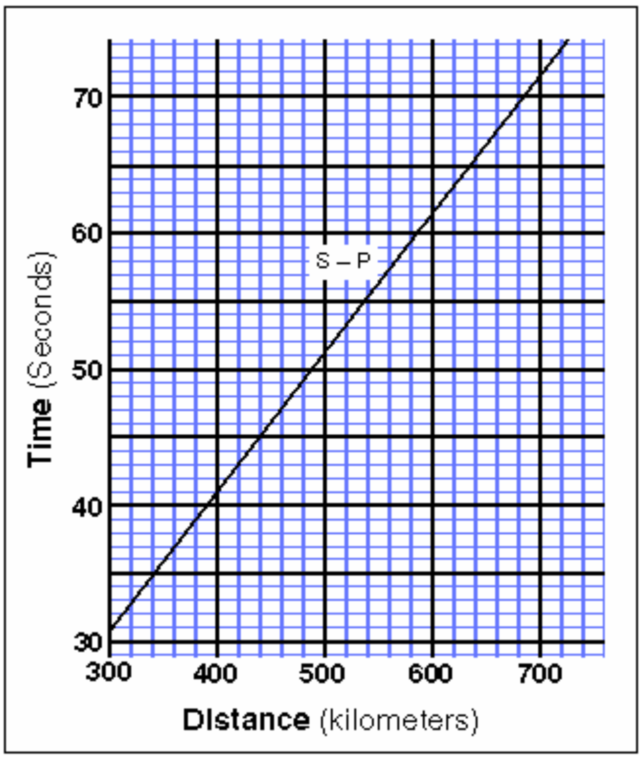


Figure 7 (left). S-P intervals for measuring the distance from the epicenter (left). From Virtual Courseware for Earth and Environmental Sciences (2002).

Step 4. Determining distance from S-P waves

Use the S-P graph (Fig. 7) and calculations you made for the S-P time intervals for the three seismograms to determine the distance from the epicenter to the three seismic stations. Record your findings in Table 1.

Step 5. Locating the epicenter

Take a draftsman compass and use the scale bar on the map (Fig. 8) to set the compass to equal the distance from each station to the epicenter. Then draw arcs around each station. The three arcs should intersect at a single point which is the epicenter. Clearly mark the location of the epicenter. Three stations are needed to triangulate the location.

Figure 8. Map for locating the epicenter of the earthquake.
From Virtual Courseware for Earth and Environmental Sciences (2002).

Question 4. Is there a known fault near the epicenter that is likely to have slipped to create the earthquake? If so, name the fault.

A. New Madrid Fault
B. Rio Grande Fault
C. San Andreas Fault

Part IV. Determining the magnitude of an earthquake – ELABORATE

One way earthquakes are recorded is the magnitude scale, which represents the energy released during the earthquake. This scale is based on the amplitude, or height, of seismic waves on a seismogram. The scale was originally called the Richter scale after Charles F. Richter, who developed it in 1935. Today, the Moment magnitude scale has replaced the Richter scale for large earthquakes. This uses the **amplitude of the seismic waves** (as the Richter scale does) but also calculates the **distance the fault moved** to determine how much energy was released.

The magnitude scale is logarithmic. For example, a magnitude 2 earthquake produces 10 times the ground motion of a magnitude 1 earthquake, and a magnitude 3 earthquake produces 100(10 × 10) times the ground motion of a magnitude 1 earthquake. **A ten-fold increase in ground motion corresponds to about a thirty-fold increase in energy released** by an earthquake. For example, a magnitude 2 earthquake releases 30 times more energy than a magnitude 1 earthquake, and a magnitude 3 earthquake releases 900 (30 × 30) times the energy of a magnitude 1 earthquake.

The magnitude of an earthquake is a unitless number, determined from the amplitude of the S-wave, adjusted for the distance between the epicenter and the seismograph station. The largest earthquake on record has a magnitude of 9.1. Such an earthquake is rare. Small earthquakes are more common than large earthquakes.

Question 1. What factors would you look for to measure the size of an earthquake?

A. Measuring the amplitude, or height, of seismic waves on a seismogram, which represents the energy released during the earthquake.
B. Measuring the displacement along the fault along which the earthquake occurred.
C. Both A and B.

Question 2. What sort of damage do earthquakes cause?

A. Cracks in the ground
B. Uplift of the land
C. Damage to structures (buildings, bridges, roads)
D. All of the above

Step 1. Watch the video Pasta Quake: Modeling Magnitude Scale Using Spaghetti
https://www.youtube.com/watch?v=64Wzr2nFkUU

On the Moment magnitude scale, each different number is a measure of the total energy released by an earthquake, and the energy increases by a multiple of about 30 between numbers of the scale. This can be demonstrated with uncooked spaghetti noodles:

Pasta magnitude scale	Number of spaghetti pieces broken
4	1/30
5	1
6	30
7	900
8	30,000
9	900,000

Step 2. Review the list below of some major earthquakes and their Moment magnitude ratings.

Question 3. Put an **X** next to the strongest one with the highest magnitude.

Question 4. Put a **Y** next to the three earthquakes that released about 30 times more energy than the Mexico City quake of 1985.

Question 5. Put a **Z** next to the earthquakes that released about 900 times less energy than the 2011 Tōhoku, Japan quake.

Option	Year	Location	Magnitude
1	1811-1812	New Madrid (Midwestern US)	8.1
2	1906	San Francisco, CA	7.7
3	1960	Arauco, Chile	9.5
4	1964	Anchorage, AL	9.2
5	1971	San Fernando, CA	6.7
6	1985	Mexico City, Mexico	8.1
7	1989	San Francisco, CA	7.0
8	1995	Kobe, Japan	6.9
9	2004	Sumatra, Indonesia	9.1
10	2010	Haiti	7.0
11	2011	Tōhoku, Japan	9.0

Step 3. To determine the magnitude of the Elko, NV, earthquake from **Part II**, measure the maximum amplitude of the S-waves from the 3 seismograms in Figure 5, and enter the results in Table 1. Figure 9 shows how to make the measurement of the S-wave's maximum amplitude.

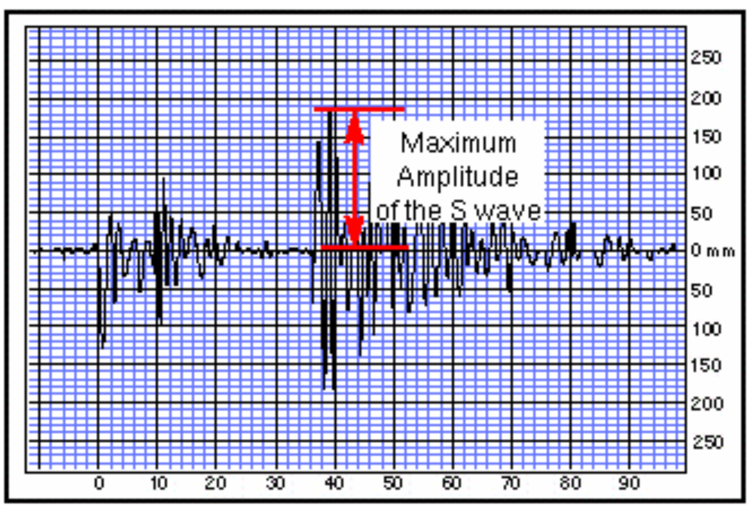


Figure 9. Seismogram labeling the maximum amplitude of S-waves. In this example the maximum amplitude is about 185 mm. From Virtual Courseware for Earth and Environmental Sciences (2002).

Step 4. Use the graphical device (called a nomogram; Fig. 10) to determine the Richter magnitude of the Elko, NV, earthquake as indicated by the data from three seismograms compiled in Table 1. On the diagram mark the distance and amplitude for each location to determine the earthquake magnitude. The distance and amplitude for the Eureka location has already been plotted. The data from each seismogram should converge on a single answer.

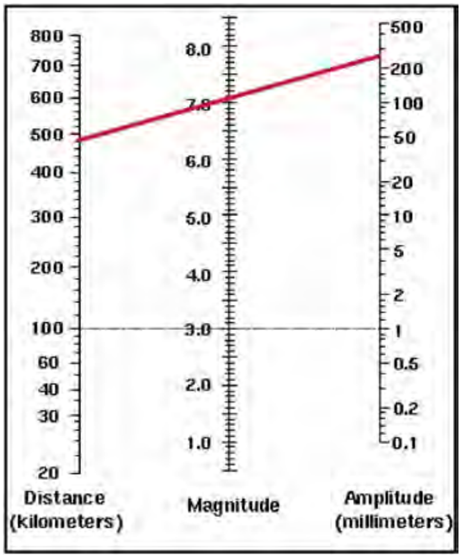


Figure 10. In the nomogram the dotted line represents the "standard" Richter earthquake. This standard earthquake is 100 km away and produces 1 mm of amplitude on the seismogram. It is assigned a magnitude of 3. Other earthquakes can then be referenced to this standard.

Note that a 100 km-away earthquake of magnitude 4 would produce 10 mm of amplitude and a magnitude 5 would produce 100 mm of amplitude: 1, 10, and 100 are all powers of 10, and this is why the Richter Scale is said to be exponential. A change of one unit in magnitude (say, from 4 to 5) increases the maximum amplitude by a factor of 10. From Virtual Courseware for Earth and Environmental Sciences (2002).

Question 6. Based on the results from mapping your data on the nomogram above (Fig. 10), what was the magnitude of the earthquake? The Eureka, CA, earthquake has been mapped onto the nomogram already. Plot the Elko and Las Vegas earthquakes onto the nomogram to confirm your answer.

A. 6.9 B. 7.0 C. 7.1 D. 7.2

Part V. Predicting earthquakes – EXPLORE 2

Geoscientists use probability of an earthquake to describe potential earthquake effects for a given location. This information allows them to determine the seismic hazard or the likelihood of a certain level of ground shaking for a region. Once the seismic hazard is calculated, the seismic risk can be estimated by determining the potential effects of the shaking on buildings and other structures.

Question 1. In Table 2, convert the probability of a magnitude 7 earthquake occurring within 50 km of two locations over different time frames to a percentage (%) chance, and answer the following questions.

Table 2.

Time Span	Magnitude	San Bernardino, CA		New Madrid, MO	
		Probability	% Chance	Probability	% Chance
1 year	7	0.01	1%	0	0%
5 years	7	0.08	8%	0.01	1%
10 years	7	0.15		0.02	
25 years	7	0.3		0.06	
50 years	7	0.6		0.12	
100 years	7	0.8		0.2	
500 years	7	0.9		0.6	
1000 years	7	0.9		0.9	

Question 2. What are the probabilities of earthquake occurrence in the above table based on?

A. The strain buildup in the area.
B. The rate of past earthquake occurrence in the area.
C. The magnitude of P-waves recorded at the nearby seismic station.
D. The location of the most recent earthquake only.

Question 3. Which region would you say has the greatest chance of experiencing a magnitude 7 earthquake?

A. San Bernardino, CA
B. New Madrid, MO

Question 4. How do the probabilities of a magnitude 7 quake change over time?

A. The probabilities decrease with an increasing time frame in the same way for both cities.
B. The probabilities increase with an increasing time frame in the same way for both cities.
C. The probabilities increase for both cities with an increased length of time, but the increase over time is higher for New Madrid.
D. The probabilities increase for both cities with an increased length of time, but the increase over time is higher for San Bernardino.

Question 5. Based on the data above, which of the following statements is most likely true?

A. San Bernardino, CA, has experienced more magnitude 7 earthquakes in the past than New Madrid, MO.
B. New Madrid, MO, has experienced more magnitude 7 earthquakes in the past than San Bernardino, CA.
C. San Bernardino, CA, and New Madrid, MO, have experienced the same number of magnitude 7 earthquakes in the past.

Question 6. Over what time period is the probability of a magnitude 7 earthquake the same between New Madrid, MO, and San Bernardino, CA?

A. 50 years
B. 100 years
C. 500 years
D. 1000 years

Part VI. Relating earthquake probabilities to ground shaking hazard – EXPLAIN 2

The probabilities you determined in Table 2 showed how likely an earthquake is to occur, but more information is needed to estimate how much the ground is going to shake during an earthquake. To estimate the extent of ground shaking for future earthquakes, geoscientists use earthquake recordings to develop models of ground shaking at an earthquake epicenter and how the shaking will decrease with distance from the epicenter. When the model of ground shaking intensity is combined with earthquake probability, the result is a probability of ground-shaking intensity within a given length of time, or an **earthquake hazard map**. This depicts the magnitudes and locations of likely earthquakes, how often they occur, and the properties of the rocks and sediments that earthquake waves travel through. Figure 11 shows a typical way that values from these models are represented.

Question 1. Based on Figure 11, what areas in the U.S. have the greatest earthquake hazard?

A. West Coast on the San Andreas fault.
B. Central USA near the New Madrid fault zone.
C. Areas within South Carolina, Alaska, and Hawaii.
D. All regions outlined above (A, B, C).

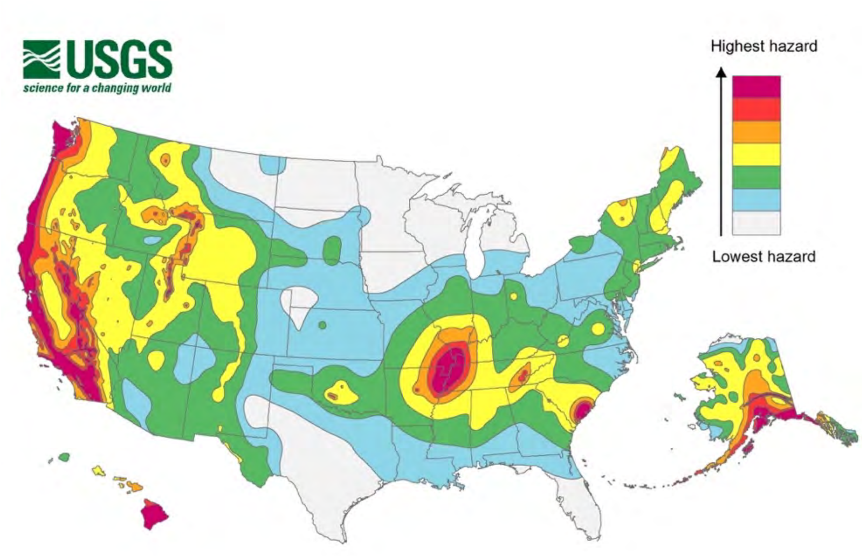


Figure 11. Earthquake hazard map of areas within the United States that have a 2% probability of experiencing a given peak ground acceleration (PGA) from an earthquake within the next 50 years. From USGS.

Part VII. Earthquakes today: Seismic Monitor – ELABORATE 2

Step 1. Go back to the IRIS Seismic Monitor website that shows earthquakes over the past five years at magnitudes greater than 2.7. http://ds.iris.edu/seismon/

Question 1. How many red circles, indicating earthquakes that happened today, are there?

B. Less than 5   B. Between 5 and 20
C. C. Between 21 and 100   D. More than 100

Question 2. Click on the largest yellow circle indicating a large earthquake that happened in the past 12 weeks. What was the magnitude of this earthquake? Where did it occur? What type of plate boundary did it form on? What was its depth?

Question 3. Where are most earthquakes located in terms of their distribution related to tectonic plates?

A. Along plate boundaries.
B. In the centers of plates.
C. On the ocean floor.
D. In Alaska.

Part VIII. Questions —EVALUATE

Question 1. What is an Earthquake? How is it generated?

Question 2. Regarding waves generated during an earthquake, which of these statements are correct?

A. Earthquakes generate different types of seismic waves.
B. Each kind of seismic wave causes a different kind of motion in the rock as it passes by and travels through rocks at different speeds.
C. The different types of seismic waves arrive at a distant point on Earth at different times.
D. All of the above.

Question 3. Earthquake magnitude (or energy released) is a measure of:

A. The amplitude of seismic waves.
B. The arrival time of primary waves.
C. People's reactions during an earthquake.
D. The severity of building damage during an earthquake.

Question 4. Which kind of earthquake waves travel the fastest through Earth?

A. P-waves
B. S-waves
C. Surface waves
D. C-waves

Question 5. How much more energy is released by an earthquake with a magnitude 9.0 compared to a magnitude 7.0 earthquake?

A. About 1 times the energy released
B. About 30 times the energy released
C. About 900 times the energy released
D. About 30,000 times the energy released

Question 6. What is a seismogram?

A. An instrument that is attached to the Earth and records the ground motion at that location.
B. A record of seismic waves recorded by a seismograph.
C. A seismic wave.

Question 7. What does a seismic hazard map represent?

A. How unlikely an earthquake is to occur in the next 50 years.
B. Areas that have a 2% probability of experiencing a given vertical ground acceleration or greater from an earthquake within the next 50 years.
C. How many earthquakes have been recorded at a given location over the past 50 years.

Question 8. Based on the Seismic Monitor website, how often are earthquakes occurring around the world?

A. Daily
B. Weekly
C. Yearly
D. Over Millennia

Exercise sources

Exercises for Part II Introduction to seismic waves and Part III Analyzing seismic data and locating an epicenter is adapted from Virtual Courseware for Earth and Environmental Sciences (2002). Part IV Determining the magnitude of an earthquake is based on materials from Exploratorium Teacher Institute and materials produced by the IRIS Consortium (Revised by Robert Butler (University of Portland) and Roger Groom (Mt. Taber Middle School, Portland)). Part V Predicting earthquakes is based on materials produced by IRIS consortium.

Sources

Doherty, P. (2021, October 8). Pasta quake. Exploratorium Teacher Institute. Retrieved January 7, 2022, from https://www.exploratorium.edu/snacks/pasta-quake

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2018 long-term National Seismic Hazard Map. 2018 Long-term National Seismic Hazard Map | U.S. Geological Survey. (n.d.). Retrieved January 7, 2022, from https://www.usgs.gov/media/images/2018-long-term-national-seismic-hazard-map

Image sources

Figure 1. Earthquake glossary. U.S. Geological Survey. (n.d.). Retrieved January 7, 2022, from https://earthquake.usgs.gov/learn/glossary/?term=fault

Figure 3, 5-10 are from Virtual Courseware for Earth and Environmental Sciences. (2002).

Figure 11 is from 2018 long-term National Seismic Hazard Map.

8. How do we measure geological time?

How have geologists determined the ages of the sedimentary and igneous rocks of the Newark Basin?

Purpose

The purpose of this lab is to understand the vast scale of geological time, the two ways geological time is measured (relative and absolute dating), and how geologists apply the principles of relative and absolute dating to determine the age of rocks.

Learning Objectives

After doing this lab you will be able to:

1. Explain the geological timescale and how the different units are defined based on the history of life.
2. Apply the principles of relative dating to determine an order of events for rock formation.
3. Use a model to explain how radioactive decay is a random process.
4. Apply relative and absolute dating methods to determine the age of rocks.

Part I. How have geologists determined the ages of the sedimentary and igneous rocks of the Newark Basin? – ENGAGE

About 250 million years ago, New York was part of Pangea which was starting to break-up. As the supercontinent pulled apart, fault bounded basins developed near Newark, New Jersey and Hartford, Connecticut. The basins filled with sediments that later lithified to form conglomerates, sandstones and mudstones. At this time the climate was hot and dry and the valleys of the Newark and Hartford Basins were filled with lakes and rivers that provided dinosaurs and other animals with a place to eat and drink. We know this because of fossilized footprints found preserved in the rocks that formed in these basins (Fig. 1).

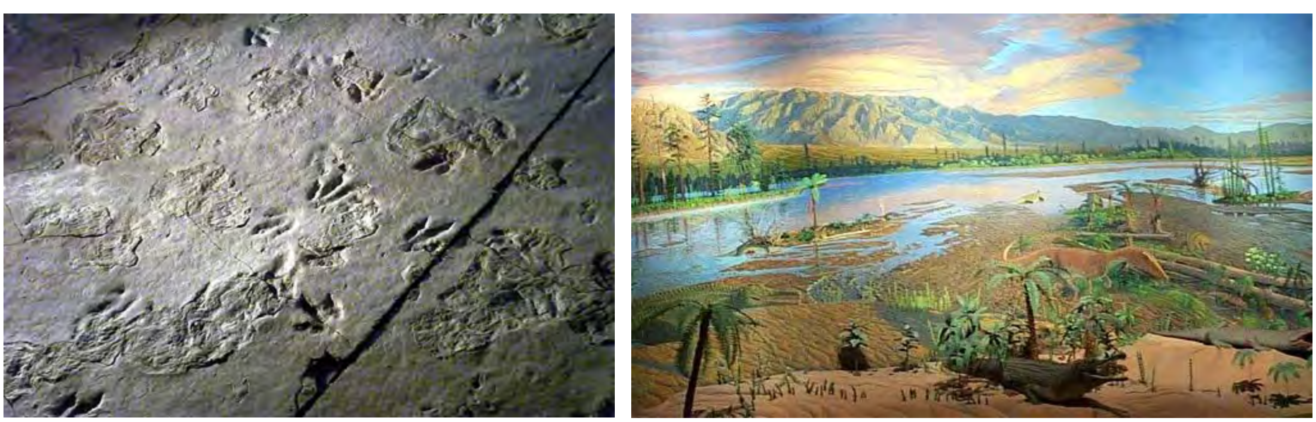


Figure 1. (a – left) Dinosaur footprints preserved in mudstone at Dinosaur State Park, Connecticut and (b- right) a rendering from the Dinosaur State Museum of what the environment might have been like 250 million years ago when dinosaurs roamed over the area. From Hansen (2002).

About 200 million years ago, as Pangea continued to pull apart, large volumes of basaltic lava erupted from volcanoes and intruded between the layers of Newark Basin sediments to form structures such as the Palisades sill (Fig. 2).

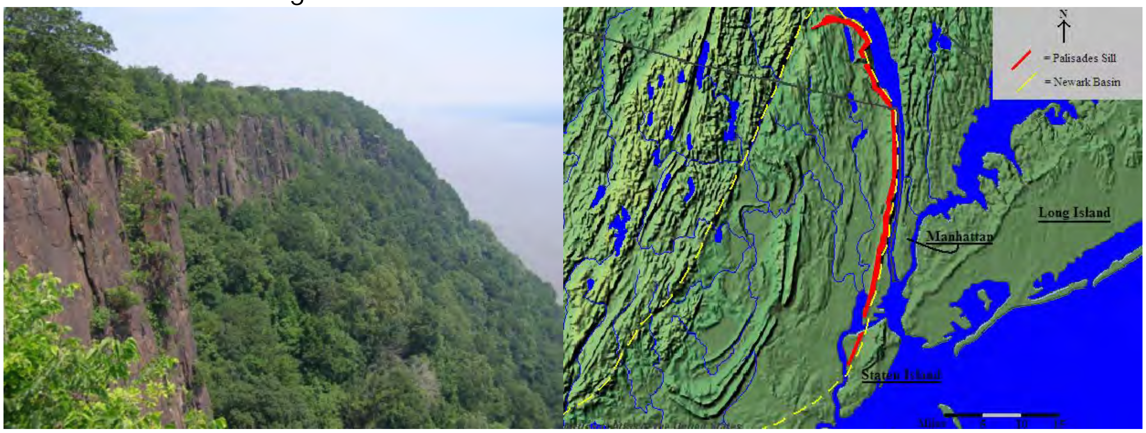


Figure 2. (a) The Palisades sill, a 300-meter-tall cliff overlooking the Hudson River (left) and (b) geologic extent in red (right). Figure. 2a is by CrankyScorpion, CC BY-SA 3.0,. Figure 2b is Public Domain.

Question 1. What are some ways geologist may have determined the ages of the sedimentary and igneous rocks of the Newark Basin? How did they connect their formation to the break-up of Pangea?

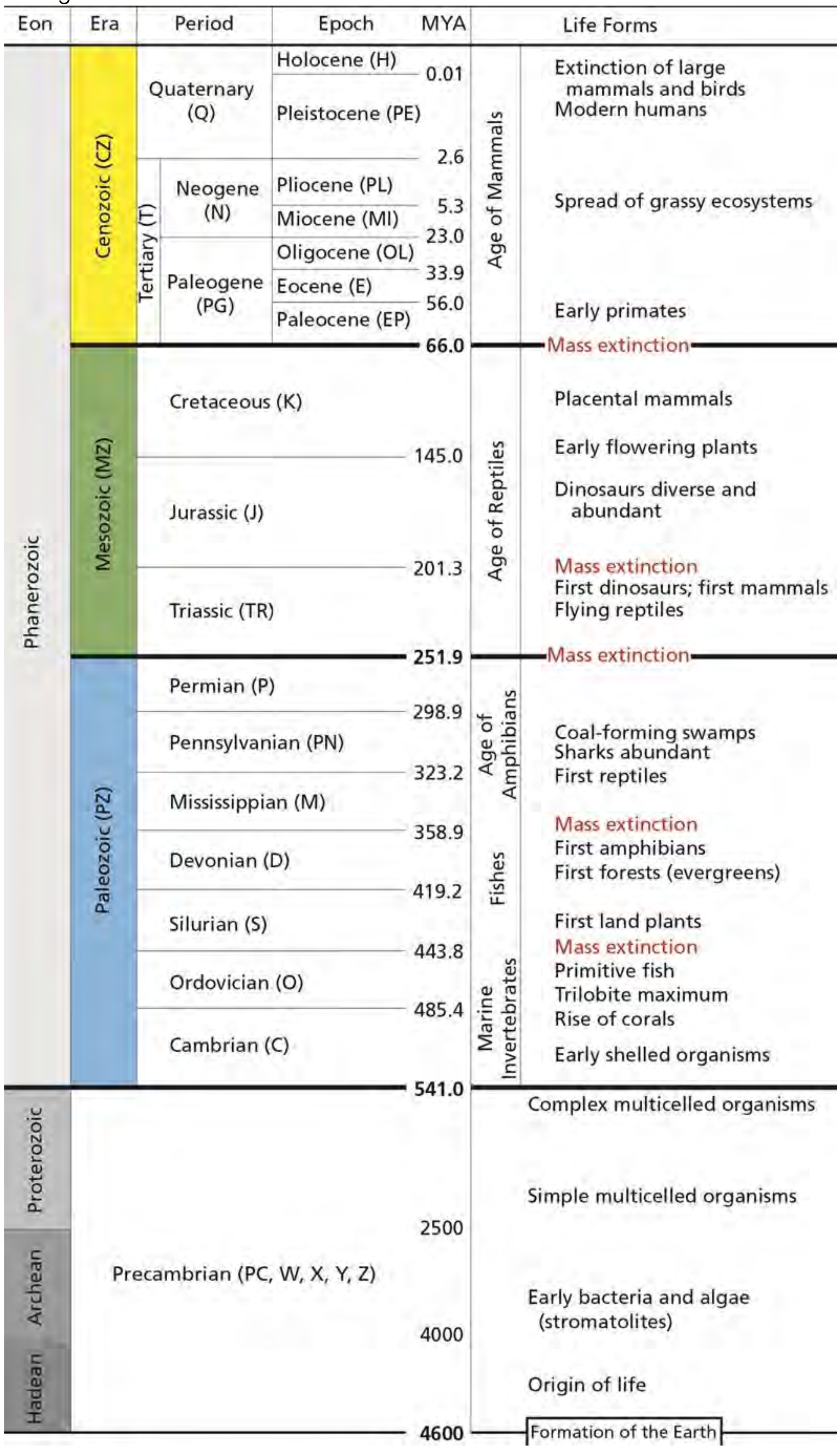
The Geological Timeline

Geological time represents the history of the Earth as recorded in the rock record. The timescale has been developed over considerable time and continues to be refined today. The time units of the geological timescale are named after locations where rocks for that age were first recognized. For example, rocks of the Pennsylvanian are named after rocks in Pennsylvania that contain coal, while Cretaceous rocks are named after rocks in Europe that contain chalk (*creta* in Latin).

The units within the geological timescale are largely named after life forms that came into being during a particular time and then died out or became extinct. For example, many lifeforms died out 251 million years ago at the end of the Permian, which is the boundary of the Paleozoic and Mesozoic. Dinosaurs thrived throughout the Mesozoic and died out about 66 million years ago to mark the boundary between the Mesozoic and Cenozoic. The Precambrian has a poor fossil record and covers most of Earth's history (4.0 billion years of the 4.6 billion year history), while the Phanerozoic has a rich fossil history that covers the past 542 million years (Fig. 3).

There are two ways in which the ages of rocks are determined. Relative ages are based on the order of events in which they occurred. Absolute or numerical ages are the age of a rock in years before present. The geologic timescale was developed using relative ages.

Figure 3. Geological Timescale. From National Parks Service



Part II. Map past life onto the geological timescale – EXPLORE

Question 1. Fill out Table 1 using the geologic timescale (Fig. 3):

Table 1

Event	Age	Geologic Time	Answer
Oldest known rocks	4100 million years ago	Eon?	
Early shelled organisms	540 million years ago	Period?	
Land Plants	430 million years ago	Period?	
First amphibians	416 million years ago	Period?	
Coal-forming swamps	318 million years ago	Period?	
First birds	175 million years ago	Period?	
Early humans	3 million years ago	Epoch?	

Question 2. An asteroid struck Earth 66 million years ago. Name the era and period just prior to this event.

Answer: Era: _______________, Period:_______________

Question 3. Dinosaurs first appeared and roamed planet Earth in the Mesozoic era starting 251 million years ago. Dinosaur extinction occurred at the end of the Mesozoic 66 million years ago. How long did Dinosaurs exist?

Answer: __________________________

Question 4. From about 1.8 million years ago until about 11,400 years ago large parts of our planet was covered with ice. What epoch does this correspond to?

Answer: __________________________

Question 5. Most of geologic time (i.e. the longest time of almost 4,000 million years) occurred during the:

A. Paleozoic Era
B. Holocene Epoch
C. Phanerozoic Eon
D. Hadean, Archean, and Proterozoic Eons known as the Precambrian

Part III. Relative dating — EXPLAIN

Before the discovery of radioactivity, geologists had no way of determining numerical or absolute ages of rocks. Instead, they relied on techniques of relative dating to put them in order. Rocks, and the fossils they contained, were found to be laid down originally as sediments in a logical order with the oldest at the bottom, which were later covered by younger and younger layers.

Figure 4a. Rock outcrop A (top).

Figure 4b. Rock outcrop B (left).

From [J. Benner, M. Blome, D. Luna, T. Rivera]

Question 1. Rock outcrop A and B (Figs. 4a & 4b) each contain two different rock types of different ages. For each outcrop (A and B), determine which of the two rock types is older and which is younger, and explain your reasoning. Use features of the rocks (like color) to describe them if you don't know the rock type name.

Rock outcrop A: relative ages of the two rocks and reasoning.

Rock outcrop B: relative ages of the two rocks and reasoning.

Step 1. Review the list of relative dating principles in Table 2. Determine which principles you think you used to determine the relative ages of the rocks in Rock outcrop A and B.

Table 2.

Principle of Geology	**Definition**
Principle of uniformitarianism:	The present is the key to the past. The physical and chemical processes that occur today (e.g., gravity, oxidation) were the same in the past.
Principle of superposition	In an undeformed sequence of sedimentary rocks, each layer is older than the one above and younger than the one below.
Principle of original horizontality	Layers of sediment are generally deposited in a horizontal position due to gravity. If they are tilted they have been disturbed.
Principle of lateral continuity	Layers of rock are continuous and extend in all directions.
Principle of crosscutting relationships:	A rock must be older than a thing that cuts across it.
Principle of included fragments	Rock that includes fragments of other rock must be younger than the fragments.

Question 2. Select the principles you used to determine the relative ages of rocks in Outcrop A.

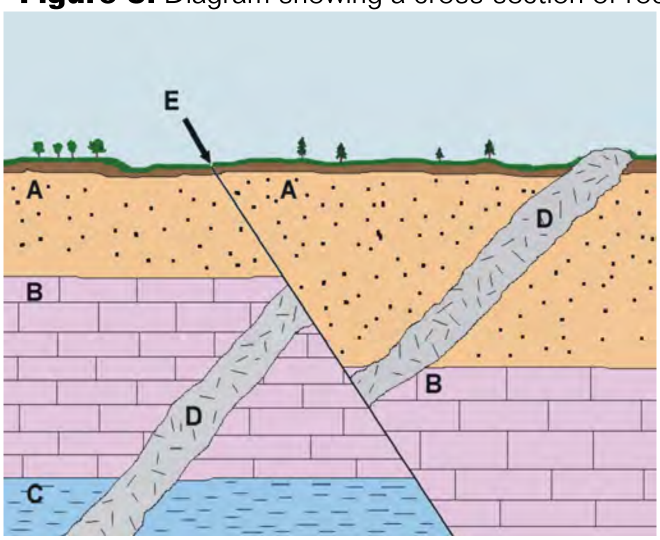
A. Uniformitarianism
B. Superposition
C. Original horizontality
D. Lateral continuity
E. Crosscutting relationships
F. Included fragments

Question 3. Select the principles you used to determine the relative ages of rocks in Outcrop B.

A. Uniformitarianism
B. Superposition
C. Original horizontality
D. Lateral continuity
E. Crosscutting relationships
F. Included fragments

Questions 4. Using the relative dating principles, in the boxes below order the units in Figure 5 from oldest to youngest.

Figure 5. Diagram showing a cross-section of rock layers. From Kurt Rosenkrantz, CC BY-SA 3.0.



Event Sequence	Letter
5. Youngest	
4.	
3.	
2.	
1. Oldest	

Question 5. Using Figure 5, which relative dating principle best describes the relationship between the dike (D) and the surrounding rock? Principle of:

A. Superposition
B. Lateral continuity
C. Cross-cutting relationships
D. Included fragments

Question 6. Using Figure 5, which relative dating principle best describes the relationship between the ages of the horizontal layers of rock (A, B, C). Principle of:

A. Superposition
B. Lateral continuity
C. Cross-cutting relationships
D. Included fragments

Part IV. Absolute dating – EXPLORE 2

Absolute ages are determined by measuring radioactive minerals that contain radioactive **isotopes**. Within minerals, the atoms of some chemical elements (such as uranium or argon) have different forms, called isotopes. If these isotopes are unstable, over time they will break down or undergo radioactive decay. The original atom, known as the **parent isotope**, will decay to form a new isotope called the **daughter** (Fig. 6).

Each element has a unique **rate of decay**. Some take thousands of years, while others take millions or billions. The amount of time it takes for one-half of a parent isotope to decay to the daughter isotope is called the **half-life**. An isotope in a rock sample can decay through about six half-lives before all the parent isotopes are transformed to daughter isotopes. When dating a rock, geologists measure the isotopes present in their rock sample. There are over 30 radiometric methods available.

You can calculate when a rock was formed if you know:

1. The rate or decay or **half-life** for a particular element
2. The amount of **parent isotopes**, and
3. The amount **daughter isotopes** in a rock.

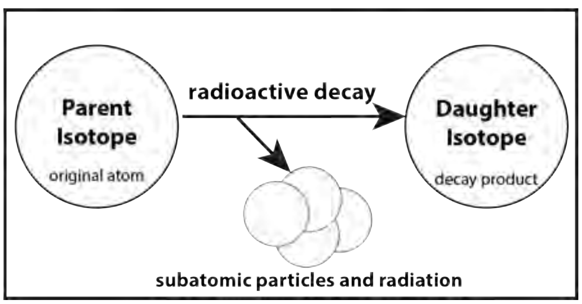


Figure 6. During radioactive decay of elements within a mineral, the original isotope (parent) releases subatomic particles to form a new element (daughter).

Question 1. Modeling radioactive decay and half-life by tossing coins

Step 1. Your instructor will assign you a student number between 1 and 16.
Step 2. Cup 10 coins in your hands. Shake and spill the coins on a flat surface.
Step 3. Count the number of heads facing up and write the number next to your student number under toss 1 in the table below.
Step 4. Put the coins with tails facing up to the side. Pick up the coins with heads facing up and return them to your hands. Repeat steps 2 to 5 until you have no more coins with heads facing-up.
Step 5. Share your results with the class in Table 3.
Step 6. Tally the class's total number of heads for each toss. Divide that number by the number of students that participated in the activity to determine the class average for each coin toss. This represents the half-life.

Table 3. Modeling half-life using coin tosses.

	Number of coin tosses. Heads remaining = radioactive parent atoms							
Student No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	10							
2	10							
3	10							
4	10							
5	10							
6	10							
7	10							
8	10							
9	10							
10	10							
11	10							
12	10							
13	10							
14	10							
15	10							
16	10							
Total coins								
Total coins/No. participants = Class Average								

Question 2. Plot your own coin toss data and your class average data on the decay curve that shows number of radioactive atoms versus half-lives (Fig. 7). How does each data set compare to the model half-life curve (black line)?

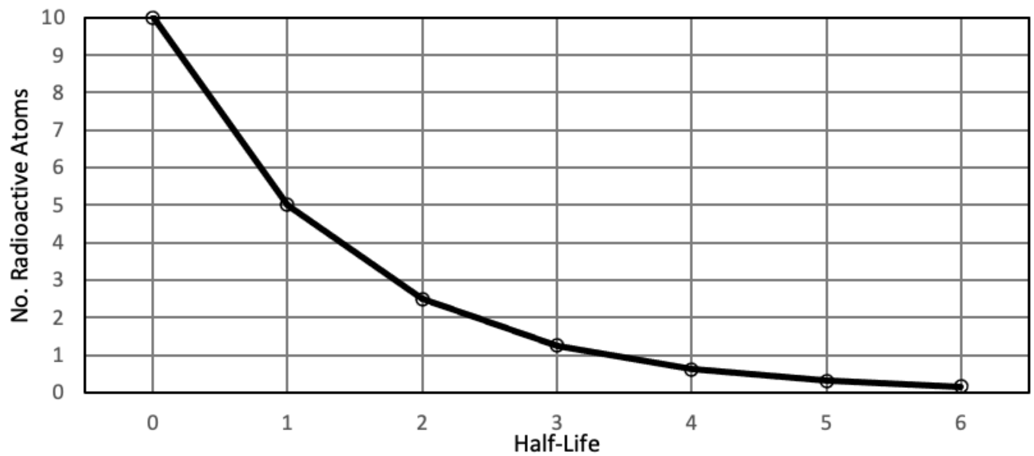


Figure 7. Radioactive decay curve showing half-lives of decaying elements, and number of heads remaining after each coin toss.

Question 3. Why do the class average values for each coin toss better show what happens during radioactive decay than your individual results?

Part V. Determining the ages of rocks containing elements H and J – EXPLAIN

Question 1. Step 1. Starting with 1000 atoms in a rock sample, calculate the number of radioactive atoms remaining after the decay of each half-life. Write the values in the Number of Radioactive Atoms row in Table 4. A graph representing the number of radioactive atoms present is provided above Table 4. Note that the number of radioactive parent atoms decreases as they transform into daughter atoms (Fig. 8).

Step 2. The half-life for hypothetical Element J is 60 million years and the half-life for Element K is 125 million years. In Table 4 write the ages of a rock containing Element J and Element K up to 7 half-lives.

Figure 8

Table 4.

Half-Life	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Number of radioactive atoms in sample	1000	500					
Half life of Element J (million years)	0	60	120				
Half life of Element K (million years)	0	125	250				

Question 2. If a rhyolite rock (sample A) contains 250 out of 1000 atoms of radioactive parent atoms of Element J, how old is the rock?

A. 60 million years old
B. 120 million years old
C. 180 million years old
D. 240 million years old

Question 3. If a basalt rock (sample B) contains 500 out of 1000 atoms of radioactive parent atoms of element K, how old is the rock?

A. 125 million years old
B. 250 million years old
C. 375 million years old
D. 500 million years old

Question 4. If your sample containing Element K is 375 million years old, how many half-lives has Element K undergone?

A. 1 half-life
B. 2 half-lives
C. 3 half-lives
D. 4 half-live

Adapted from The half-life of licorice. American Nuclear Society

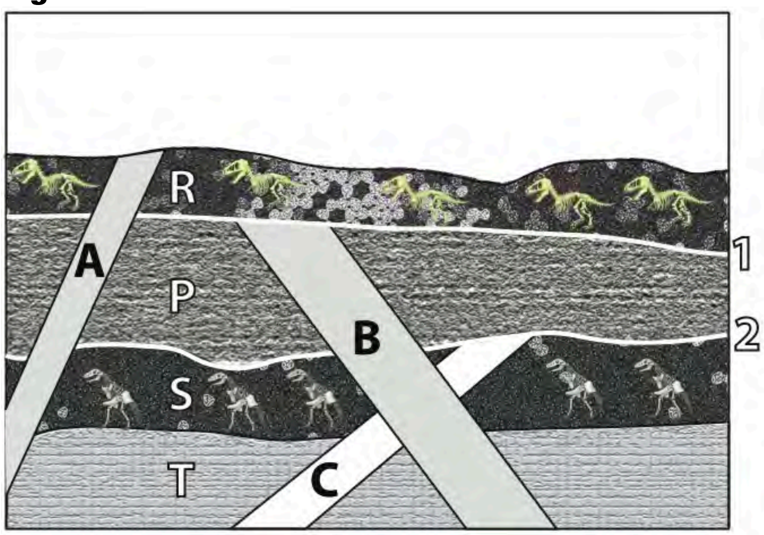
Part VI. Relative and absolute dating – ELABORATE 2

You are the lead paleontologist on an expedition to Boulder, Colorado, to document two newly discovered dinosaur fossils. To fully document this new discovery, you will need to determine the ages of the rocks containing the fossils, which will allow you to determine when these dinosaurs lived.

Question 1. Step 1. Order the rocks units in Figure 9 from oldest to youngest.
Step 2. Determine the age of the igneous rock units (A, B, C) based on the following information, and enter this information into the chart below.

> **Rock A** is a rhyolite containing 250 out of 1000 atoms of Element J
> **Rock B** is a basalt containing 500 out of 1000 atoms of Element K
> **Rock C** is a basalt containing 125 out of 1000 atoms of Element J

Figure 9



Event Sequence	Letter	Rock Age (million years)
9. Youngest		
8		
7		
6		
5		
4		
3		
2		
1. Oldest		

Question 2. What is the youngest age possible age for the dinosaur fossils in layer S?

Youngest age is more than ________million years old

Question 3. What is the oldest and youngest age possible age for the dinosaur fossils in layer R.

Oldest age is less than ________ million years and more than ________million years

Question 4. What was the break in time (as shown by the unconformity 1) between the formation of Layer R and Layer P?

_____________ million years

Question 5. How much of a break in time (as shown by the unconformity 2) was there between the formation of Layer S and Layer P?

_____________ million years

Part VII. Geology of the Newark Basin – EVALUATE

Question 1. Revisit Figure 1 and Figure 2 showing the fossil footprints in sedimentary rocks and nearby igneous rocks in New Jersey and Connecticut, which formed during the breakup of Pangea (starting 250 million years and ending about 160 million years ago) with the opening of the Atlantic Ocean. Based on what you have learned in these activities, list some ways scientists could have determined the ages of these rocks and connected them to the breakup of Pangea?

Exercise sources

Part III. Relative dating is adapted from Benner et al. (2021). Part IV. Absolute dating is adapted from The half-life of licorice (ANS).

Sources

Benner, J, Blome, M., Luna, D., & Rivera, T. (2021, September 22). Geologic time: Principles & applications. Activities. Retrieved January 7, 2022, from https://serc.carleton.edu/inquiry_intro_geo/activities/244906.html

Hansen, G. 2002. Field Trip Hartford Basin, Connecticut. https://pbisotopes.ess.sunysb.edu/lig/Field_Trips/hartford-basin/ (n.d.) Retrieved January 7, 2022.

Olsen, P. E. & Rainforth, E. C. (2001). The age of dinosaurs in the Newark Basin, with special reference to the Lower Hudson Valley. New York State Geological Association Guidebook.

The half-life of licorice. American Nuclear Society. (n.d.). Retrieved January 7, 2022, from https://www.ans.org/nuclear/classroom/lessons/

Image sources

Figure 1. Dinosaur footprints preserved in mudstone at Dinosaur State Park, Rocky Hill, Connecticut (left) and a rendering from the Dinosaur State Museum of what the environment might have been like 250 million years ago when dinosaurs roamed over the area (from Hansen, 2002).

Figure 2a. By CrankyScorpion, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2234095

Figure 2b. By Work of the United States Government. Originally uploaded on the English Wikipedia by CrankyScorpion - Original source: UnknownImmediate source: http://en.wikipedia.org/wiki/Image:Palisades_Sill_Location_Map.JPG, Public Domain, https://commons.wikimedia.org/w/index.php?curid=2234105

Figure 3. U.S. Department of the Interior. (5 October, 2021). Geologic time scale. National Parks Service. Retrieved January 7, 2022, from https://www.nps.gov/subjects/geology/time-scale.htm

Figures 4 a & b are from J. Benner, M. Blome, D. Luna, & T. Rivera (2021).

Figure 5. By Kurt Rosenkrantz - http://cafreetextbooks.ck12.org/science/CK12_Earth_Science_rev.pdf (page 420). If the above link no longer works, visit http://www.ck12.org and search for CK-12 Earth Science., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=11017657

9. Glacial Landforms of New York

How have glaciers changed New York?

How do glaciers in Alaska change the landscape?– ENGAGE

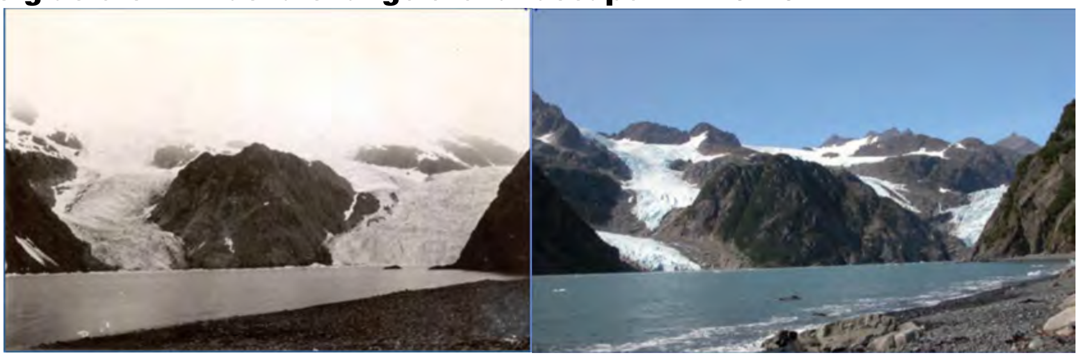


Figure 1. Holgate glacier, Alaska in 1909 and 2004. From [Glaciers, WGBH.]

Learning Outcomes:

1. Observe changes in glaciers and landscapes.
2. Sketch a glacial landscape.

Introduction

This activity features six pairs of photographs of Alaskan glaciers taken up to 100 years apart. Look at each pair of images and observe the different landform features. Use the sliders on the website to carefully observe the differences between the older and newer photos.

Step 1. Go to the Documenting Glacial Change website:
https://contrib.pbslearningmedia.org/WGBH/ipy07/ipy07-int-glacierphoto/index.html

Step 2. Use the slider to observe the differences between the older and newer photographs, and look for at least two changes in each set of pictures.

Question 1

GLACIER NAME and PHOTO DATES	What changes do you observe during the time span?
Muir Glacier Dates: August 1941 and August 2004	
Carroll Glacier Dates: August 1906 and September 2003	
Holgate Glacier Dates: July 1909 and August 2004	

Question 2

QUESTIONS	YOUR RESPONSE
1. What overall patterns do you notice between the older and newer photos?	
2. What do you think is a possible cause for the differences between the older and newer photos at the same locations?	

Question 3.

CHOOSE AN INTERESTING PART OF ONE OF THE PHOTOS AND SKETCH IT.	
Insert your sketch in this space	
A. Which photo did you sketch and what is the date?	
B. What made you decide to sketch this?	

Glacial Advance and Retreat – EXPLORE 1

Learning Outcomes:

1. Measure glacier advance and retreat.
2. Graph glacial retreat data and make an interpretation.

Glacial Advance and Retreat

Over time, glaciers advance (accumulation) and retreat (ablation). This is a function of changes in climate. As climate cools, snow and ice accumulate and glaciers advance. As climate warms, snow and ice melt and glaciers retreat. Changes to glaciers also depend on the shape of the land and, if the glacier is entering the ocean, the sea surface temperature.

We can determine the rate of glacial growth and decline by measuring the distance the front of the glacier has moved over time. **Rate = Distance (meters)/Time (years)**

Maps of the Bear, Columbia and Hubbard glaciers in Alaska are shown below. The dashed and solid lines show the inferred location of the front edge of each glacier at a given year.

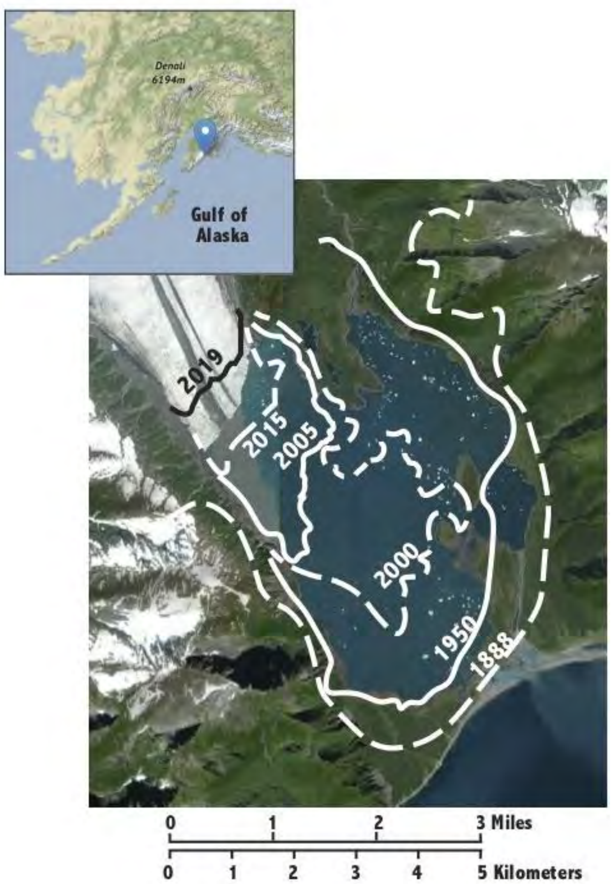


Figure 2a. The Bear glacier
Modified from NASA

Step 1. Watch the following video, “48 Years of Alaska’s Glaciers”:
https://www.youtube.com/watch?v=E4Zc_KuXMkA&t=9s

Step 2. View the maps of Bear, Columbia, and Hubbard glaciers in Alaska. Complete the chart below for the three glaciers. The distance must be measured using a ruler and the scale bar. If the glacier advanced, the distance should be positive. If the glacier retreated, the distance should be negative. Use a calculator to determine the rate of glacier movement for each time period.

Figure 2b. Columbia glacier, Alaska. Modified from NASA

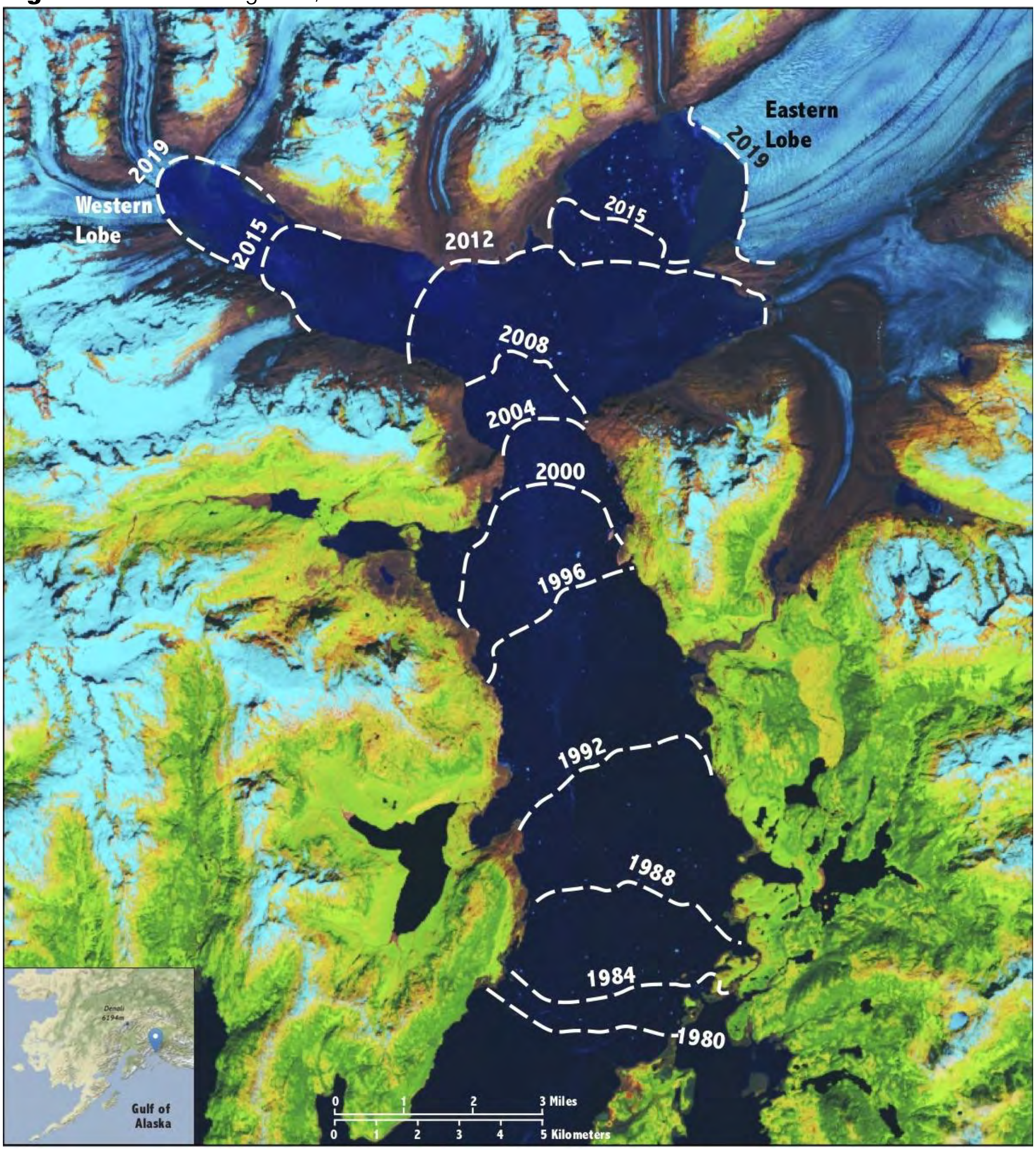
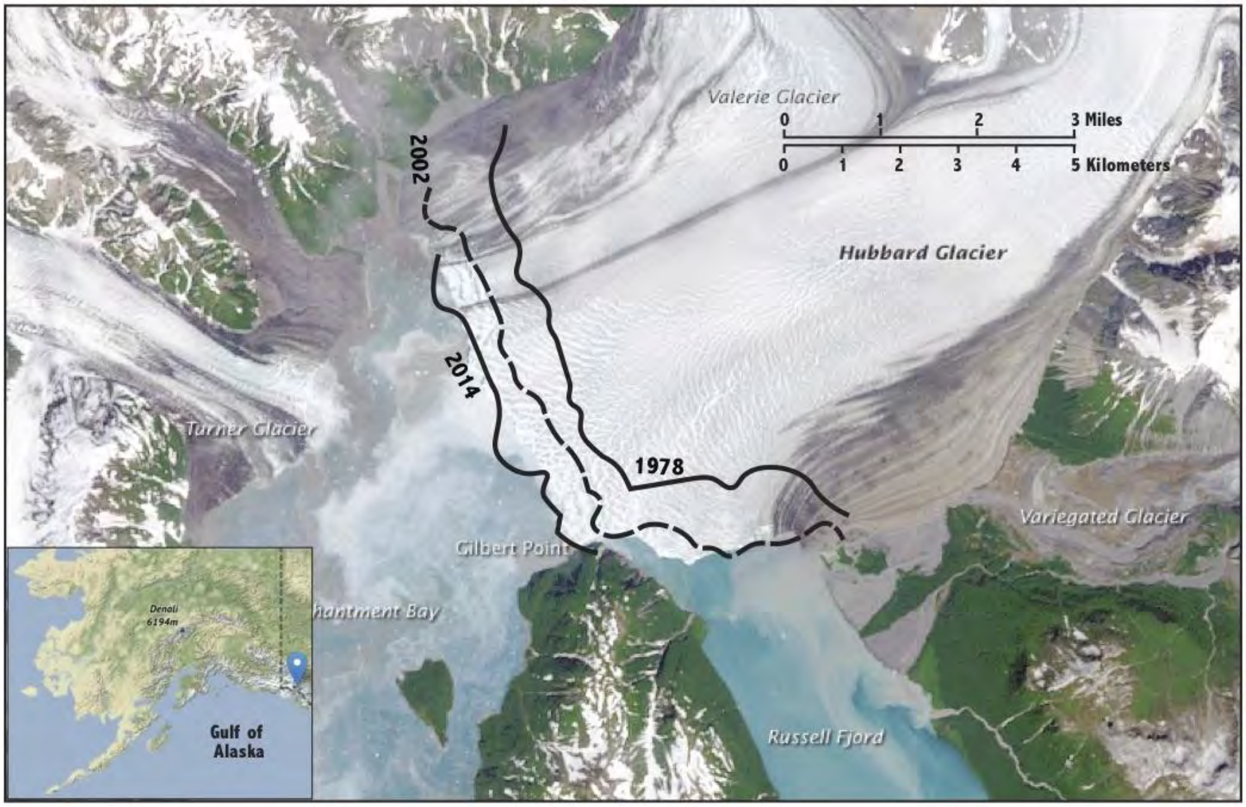


Figure 2c. Hubbard glacier, Alaska. Modified from NASA.



Question 1

Bear Glacier			
Glacial Fronts	**Time (years)**	**Distance (meters or kilometers x 1000)**	**Rate (Distance/Time) in meters/year**
1950-2000			
2000-2005			
2005-2019			
Columbia Glacier			
Glacial Fronts	**Time (years)**	**Distance (meters or kilometers x 1000)**	**Rate (Distance/Time) in meters/year**
1980-1996			
1996-2008			
2008-2019 (west lobe)			
Hubbard Glacier			
Glacial Fronts	**Time (years)**	**Distance (meters or kilometers x 1000)**	**Rate (Distance/Time) in meters/year**
1978-2002			
2002-2014			

Step 3. Answer the following questions based on the table above.

Question 2. Which glacier advanced the most distance after 1980?

A. Bear glacier
B. Columbia glacier (west lobe)
C. Hubbard glacier

Question 3. Which glacier(s) retreated after 1980?

A. Bear glacier
B. Columbia glacier (west lobe)
C. Hubbard glacier

Question 4. Which glacier advanced or retreated at the fastest rate?

A. Bear glacier
B. Columbia glacier (west lobe)
C. Hubbard glacier

Question 5. What was this rate?

A. 600 meters/year
B. 625 meters/year
C. 636 meters/year
D. 500 meters/year

Question 6. Graph the rate of retreat of the Columbia glacier from Table 2 (western lobe) using the chart below (Fig. 3) and answer the following questions.

Table 2. The rate of retreat of the Columbia glacier (western lobe).

Glacial Fronts	Time (years)	Distance (meters = kilometers x 1000)	Rate of retreat (Distance/Time - meters/year)
1980-1984	4	1000	250
1984-1988	4	3000	750
1988-1992	4	3500	875
1992-1996	4	4500	1125
1996-2000	4	3000	750
2000-2004	4	2000	500
2004-2008	4	1800	450
2008-2012	4	2800	700
2012-2015	3	4000	1333
2015-2019	3	3500	1167

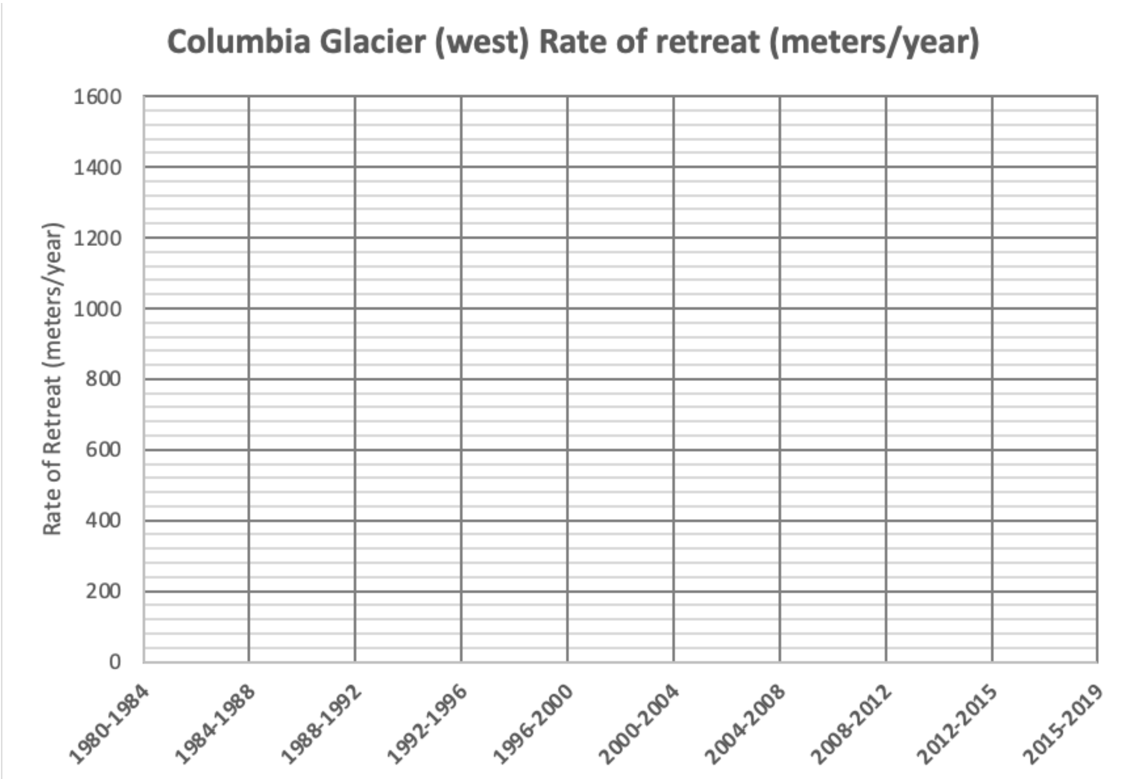


Figure 3.

Question 7. How did the rate of glacier retreat change through time?

Question 8. What could have driven this rate of glacial retreat?

Question 9. Besides changes to climate, what else could have caused a change in the rate of glacier retreat? Look at the map of the Columbia glacier to inform your answer.

How are landforms created by glaciers? – EXPLORE 2

<table>
<tr><td colspan="2">Explore 2. Question 1. Look at the image below. Add a Notice and Wonder, focusing on how you think this landform might have been created.</td></tr>
<tr><td rowspan="2">
Figure 4. Balanced rock, North Salem, NY.
From Daniel Case, Balanced rock, North Salem, NY, CC BY-SA 3.0,</td><td>NOTICE</td></tr>
<tr><td>WONDER</td></tr>
</table>

Learning Outcomes:

1. Explain how a glacial landform is created.

Classroom Demonstration (Kettle Lakes)

Figure 5. Kettle lake demonstration

Your teacher is going to model how a kettle lake is formed. In this model, we have ice cubes on a tray of sand. Predict what you think will happen over the course of the class. We will come back at various points in our class to make observations. Then, you will explain how kettle lakes form.

Question 2. Predict-Observe-Explain: What will happen to the ice cube in the container of sand over time?

Predict	Observe	Initial Explanation
What do you think WILL happen?	What do you observe happening?	Why and how did this happen?

Question 3. Video Demonstration
Watch this video about how glacial striations form: https://youtu.be/hkFUoIG06Nc

Predict	Observe	Initial Explanation
What do you think WILL happen?	What do you observe happening?	Why and how did this happen?

Question 4. Analogy Map for a Model Tool. What are the parts of the model? How is the part of the model like the part of the real world? How is the part of the model not like the part of the real world?

What are the parts of the model?	How is the part of the model like the part of the real world?	How is the part of the model not like the part of the real world?

Question 5. Explain how one glacial landform is created using examples from the models of the kettle lake or glacial striations, grooves and erratics used in today's class

How do glaciers change the landscape? – EXPLAIN

Learning Outcomes:

1. Sketch glacial features.
2. Create a group analogy for a glacial feature.

Introduction

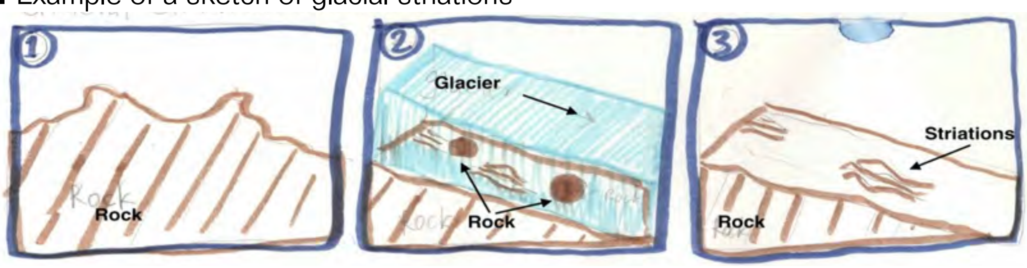
The land surface of New York has been shaped by the movement of glaciers. Mile high ice sheets or glaciers covered New York between 100,000 and 10,000 years ago during the Pleistocene glaciation. These thick sheets of ice would have towered above the Empire State Building. They carved the landscape like a giant bulldozer, smoothing it out and picking up and carrying rocks as big as a truck. Glaciers both weather and erode the landscape and deposit debris on the landscape. We can find evidence for glacial erosion and deposition features right in our own urban backyard.

Step 1. Form a group of four.
Step 2. Each group member will be assigned one glacial feature to become an expert on.
Step 3. Each group member will sketch how their glacial feature formed in a three-step time sequence.
Step 4. Each group member will share their three-step sequence with their small group and as a group, create an analogy for each feature and describe how it represents the feature. It can relate to food, machines, computers, or anything you know a lot about.
Step 5. Share one sketch and one analogy with the class.

Glacial features:

1. Striations and grooves
2. Pothole
3. Roche Moutonnee
4. Erratic
5. Moraine
6. Kettle lake

Figure 6. Example of a sketch of glacial striations



Example of description of how feature formed

Glacial Feature	Stage 1	Stage 2	Stage 3
Glacial striations	Jagged rock in the ground.	A glacier moves over the rock and smooths it. Rocks trapped at the base of the glacier scratch the surface of the underlying rock.	The glacier melts and exposes the smooth rock with lines or striations.

Analogy - How does this analogy represent this feature?
Scraping a cucumber with a fork represents glacial striations because the whole cucumber is like the bedrock and the lines from the fork represent the scratches made by rocks sticking out of the bottom of the glacier that scratch the surface as the glacier moves. 

Explain. Question 1. Sketch of glacial feature 1

1.	2.	3.

Explain. Question 2. Description of how glacial feature formed

Glacial Feature	**Stage 1**	**Stage 2**	**Stage 3**

Analogy - How does this analogy represent this feature?

Notes

Glacial Feature	Definition	Analogy
1. Striations and grooves		
2. Pothole		
3. Roche Moutonnee		
4. Erratic		
5. Moraine		
6. Kettle lake		
7. Outwash plain		

Field trip to explore New York's glaciated landscape – ELABORATE

Learning Outcomes:

1. Identify and interpret evidence for glacial activity at locations in New York State.
2. Connect glacial evidence to past climate.

Step 1. Open either the following Google Maps https://tinyurl.com/4csusjcw
or Google Earth https://tinyurl.com/9284vdhc
Click "Present" to get started.
Step 2. Using the "Landforms of New York" menu, choose four locations to visit.
Step 3. Answer the following questions about each location. (Part I)
Step 4. Answer the question about past climate. (Part II)

Question 1. Match locations to glacial features.
Location 1: Location Name:

A. Umpire Rock
B. Inwood Hill Park
C. Riverdale Playground
D. Oakland Lake
E. Shelter Rock
F. Lake Ronkonkoma
G. Montauk Point
H. Bear Mountain
I. Storm King

Question 2. What glacial evidence do you see at this location?

A. Striations and grooves
B. Pothole
C. Roche Moutonnee
D. Erratic
E. Moraine
F. Kettle lake

Question 3. Propose how this feature may have been formed by a glacier.

Question 4.

Location 2: Location Name:

A. Umpire Rock
B. Inwood Hill Park
C. Riverdale Playground
D. Oakland Lake
E. Shelter Rock
F. Lake Ronkonkoma
G. Montauk Point
H. Bear Mountain
I. Storm King

Question 5. What glacial evidence do you see at this location?

A. Striations and grooves
B. Pothole
C. Roche Moutonnee
D. Erratic
E. Moraine
F. Kettle lake

Question 6. Propose how this feature may have been formed by a glacier.

Question 7.

Location 3: Location Name:

A. Umpire Rock
B. Inwood Hill Park
C. Riverdale Playground
D. Oakland Lake
E. Shelter Rock
F. Lake Ronkonkoma
G. Montauk Point
H. Bear Mountain
I. Storm King

Question 8.

What glacial evidence do you see at this location?

A. Striations and grooves
B. Pothole
C. Roche Moutonnee
D. Erratic
E. Moraine
F. Kettle lake
G. Outwash plain

Question 9. Propose how this feature may have been formed by a glacier.

Question 10.
Location 4: Location Name:

A. Umpire Rock
B. Inwood Hill Park
C. Riverdale Playground
D. Oakland Lake
E. Shelter Rock
F. Lake Ronkonkoma
G. Montauk Point
H. Bear Mountain
I. Storm King

Question 11.
What glacial evidence do you see at this location?

A. Striations and grooves
B. Pothole
C. Roche Moutonnee
D. Erratic
E. Moraine
F. Kettle lake
G. Outwash plain

Question 12. Propose how this feature may have been formed by a glacier.

Question 13. What does this tell us about New York's history? How does this connect to the past climate?

Expeditions to document glacial landscapes – EVALUATE

Learning Outcomes:

1. Write a detailed report as a lead scientist.
2. Describe and sketch glacial landforms.
3. Describe and sketch glacial formations and processes.

Instructions: Choose an option below and write a detailed report as the lead scientist working on the project. Include scientific sketches of glacial landforms and processes you identify.

Option 1

You are the lead geologist on a National Geographic expedition to document the disappearing glaciers of Glacier National Park. You are journaling what you observe each day and taking measurements of the last remaining glaciers. Write a report that describes the landscape. Include two or more features that indicate glaciers were once common in the region and describe how they formed. What should visitors look for in the future? Use either Google Earth or Google Maps in satellite view to identify landforms.

Option 2

You are an Earth science professor at CUNY in the year 2050, and there are no mountain glaciers left. You want to take your students on a field trip to the Peruvian Andes to convince them that glaciers once existed. Write a field trip proposal that describes where you will take students, what they would see, and what you would tell them. Include two or more features that indicate past glacial presence. Use Google Earth to virtually navigate the Cordillera Blanca to write your proposal.

Option 3

You are the principal investigator at NASA for the next Mars mission. It is your job as the lead scientist to propose where to send the next rover. You are investigating whether ice was once present on the surface of Mars, and you have to comb through preliminary data and existing images to help you narrow down where to send the rover. Write a proposal that indicates where the rover should land to look for glacial evidence and what led you to that decision. Include two or more landforms that indicate the possibility of glaciers, and describe how they formed. Use Google Mars to identify potential landforms. http://marspedia.org/images/4/48/USGS-PlanetMars-TopographicalMap.png

Rubric

	Needs Improvement	**Basic**	**Proficient**	**Exemplary**
Writing	Writing is unclear and does not convey the scientist's point of view.	Writing is unclear but conveys the scientist's point of view.	Writing uses full sentences and is written from a scientist's point of view.	Writing is clear, uses full sentences, and is clearly written from a scientist's point of view.
Landform Description	Landforms are not described, and sketches and illustrations are not included.	One landform is described but sketches and illustrations are included.	Two landforms are briefly described and sketches and illustrations are included.	Two landforms are clearly described and sketches and illustrations are included.
Landform Formation/ process	How landforms are formed is not described, and sketches and illustrations are not included.	How landforms are formed is not described but sketches and illustrations are included.	How both landforms are formed is briefly described and sketches and illustrations are included.	How both landforms are formed is clearly described and sketches and illustrations are included.

Sources

Davies, R. M., Wolk-Stanley, J. Yuan, V., Contino, J. (2021) Engaging New York City students in climate change science using a place-based 5E mini-unit on glacial evidence. The Earth Scientist, Volume XXXVIII, Issue 4, Winter 2021.

Figure sources

Figure 1. Glaciers. (n.d.). WGBH. https://contrib.pbslearningmedia.org/WGBH/ipy07/ipy07-int-glacierphoto/index.html.

Figure 2a. The Bear glacier from NASA. (2005, August 8). Bear glacier, gulf of Alaska. NASA. Retrieved January 7, 2022, from https://www.earthobservatory.nasa.gov/images/7097/bear-glacier-gulf-of-alaska

Figure 2b. The Columbia glacier from NASA. (n.d.). https://earthobservatory.nasa.gov/world-of-change/ColumbiaGlacier/show-all. NASA. Retrieved January 7, 2022, from https://www.earthobservatory.nasa.gov/images/7097/bear-glacier-gulf-of-alaska

Figure 2c. The Hubbard glacier from NASA. (n.d.). The advance of Hubbard Glacier. NASA. Retrieved January 7, 2022, from https://earthobservatory.nasa.gov/images/85900/the-advance-of-hubbard-glacier

Figure 4. From Daniel Case, Balanced rock, North Salem, NY, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1141378

10. Geography and Landforms of New York

How did Long Island get its shape?

Purpose

The purpose of this lab is to become familiar with the geographical locations of the boroughs of New York City and counties of Long Island and the landform characteristics of the provinces of New York State. The lab focuses on the landforms of Long Island, which formed by glacier advance and retreat and coastal processes.

Learning objectives

After doing this lab you will be able to:

5. Identify the boroughs of New York City and the counties of Long Island on a map.
6. Explain how glacial and sedimentary processes formed Long Island, NY.
7. Map rock types of Long Island onto a map and draw a topographic profile.
8. Define latitude and longitude and read coordinates from an online map.
9. Describe erosion and depositional features that created the landform of Long Island, NY.

Part I. Landforms found in New York City and Long Island – ENGAGE

Figure 1. NASA Landsat satellite mosaic image of Long Island, NY.

Question 1. What do you know about the types of rocks we have on Long Island? How did Long Island get its topography and shape? Observe Figure 1 to generate some ideas.

Part II. Geography of New York City and Long Island – EXPLORE 1

Question 1. Using the map of New York City (Fig. 2), label the five boroughs: Bronx, Brooklyn, Manhattan, Queens, Staten Island.

A. ____________
B. ____________
C. ____________
D. ____________
E. ____________

Answer questions 2 to 6 using the locations (A-E) listed below.

Question 2. What location is shown by F? ____________
Question 3. What location is shown by G? ____________
Question 4. What location is shown by H? ____________
Question 5. What location is shown by I? ____________
Question 6. What location is shown by J? ____________

I. New Jersey
II. Long Island
III. The Hudson River
IV. The Long Island Sound
V. The New York Harbor (Atlantic Ocean)

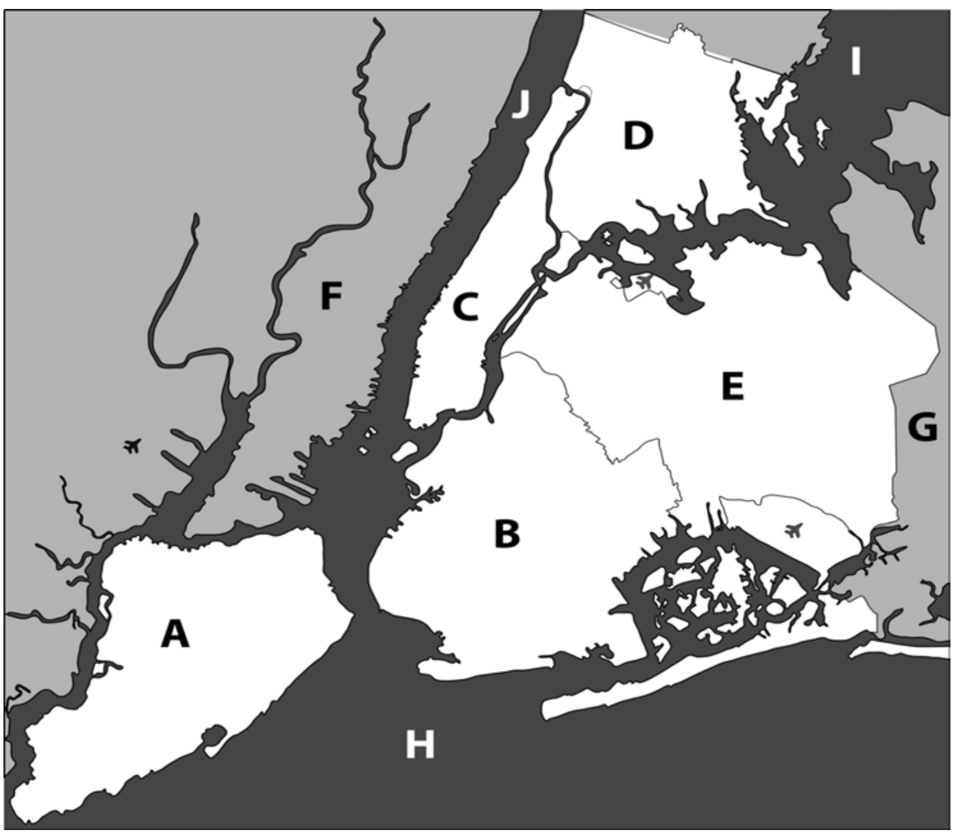


Figure 2. The boroughs and waterways of New York City.

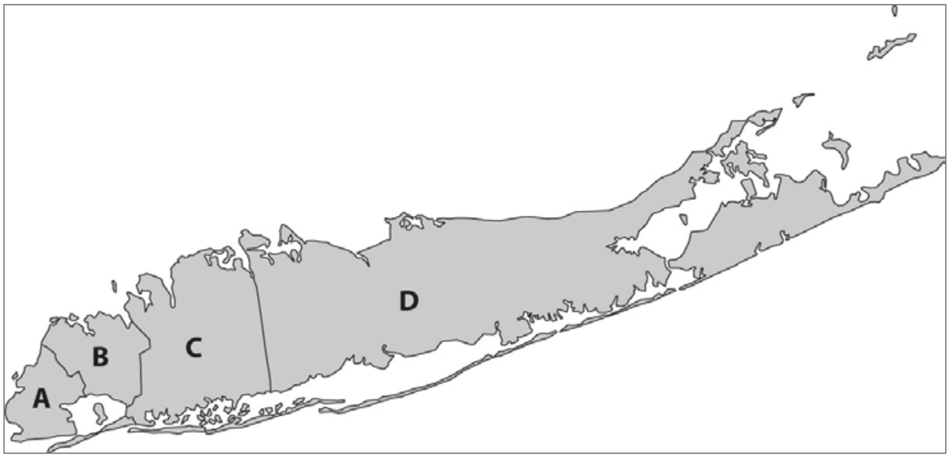


Figure 3. Map of Long Island.

Question 7. Use Figure 3 to connect the letters on the map to the locations Brooklyn, Queens, Nassau County, and Suffolk County.

A. ____________ B. ____________ C. ____________ D. ____________

Part III. Landforms and Geology of the New York City Area – EXPLAIN

New York State is made up of diverse landscapes with more than a billion years of history. The rocks of New York formed through a series of plate tectonic collisions that created tall mountain ranges through time. These mountains are now largely eroded away, leaving their traces in the form of metamorphic basement rocks that underlie the entire state and are blanketed by large regions of sedimentary rocks.

Question 1. Using the geology map of New York State (Fig. 4) fill in Table 1 below.

Table 1.

Landform Name	Basement rock type (igneous, metamorphic, sedimentary)	Age of basement rock in periods and eras	Ages
1. Atlantic Coastal Plain			70 million to 10,000 years
2. Newark and Hartford Basin	Sedimentary		195 million years ago
3. Manhattan Prong			550-440 million years ago

Question 2. How old are the oldest rocks in New York State? Hint: In Figure 4 the oldest rocks are at the bottom of the map key; younger rocks are at the top.

A. Cambrian
B. Cretaceous
C. Late Triassic
D. Middle Proterozoic
E. Ordovician
F. Pleistocene

Question 3. Based on the basement geology map (Fig. 4), what rock types are most abundant in New York State?

A. Igneous and metamorphic
B. Metamorphic and sedimentary
C. Sedimentary and igneous

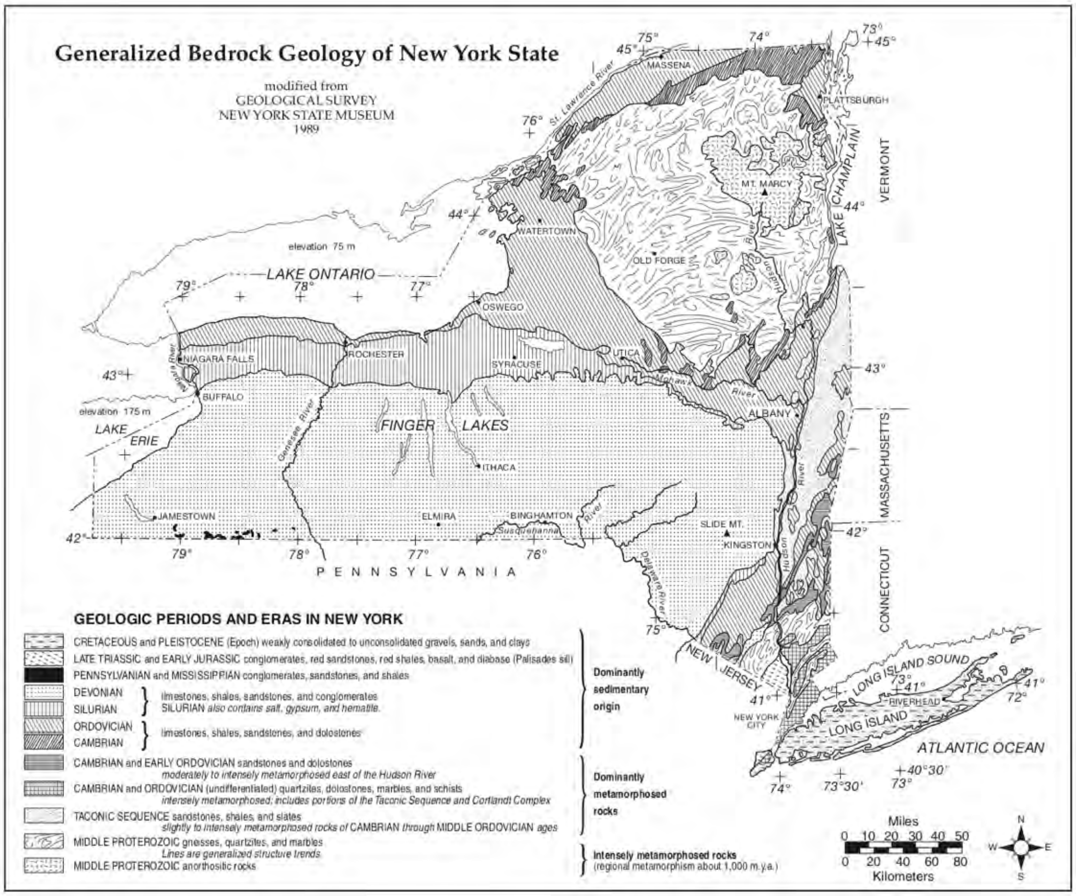


Figure 4. Geology of New York State.
From [reference tables for physical setting/earth science](). New York State Education Department.

Question 4. What rock types are found in the landform in which you reside? Use information gathered from the text below to briefly describe how this area was formed.

1. The Atlantic Coastal Plain

One of the most significant and recent factors to shape the landscape of much of New York State has been the work of continental ice sheets during the most recent glacial period. Starting about 100,000 years ago, the Wisconsin ice sheet or glacier advanced south to Long Island and only retreated from this region between 10,000 and 15,000 years ago.

The Atlantic Coast Plain, which makes up Long Island, is the youngest province in New York. It is made up of unconsolidated sediments deposited by recent coastal and glacial processes. The underlying rocks of Long Island are made of Cretaceous sediments (Coastal Plains sediments) that were deposited over older metamorphic basement rocks about 70 million years ago. These sediments are the source of several groundwater storage aquifers on the island (Fig. 5).

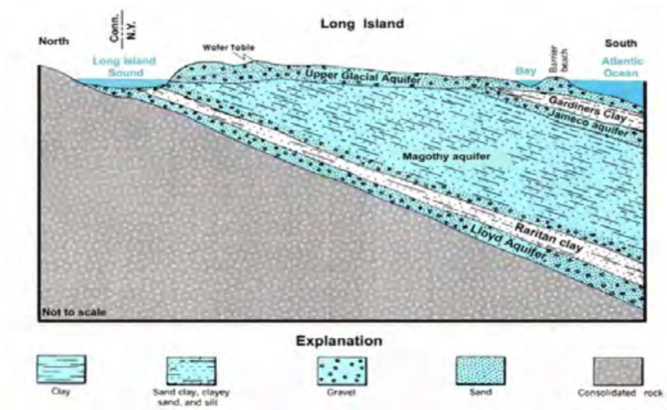


Figure 5. A cross-section of Long Island with the basement rocks (gray), sediments (tilted layers), glacial rocks (horizontal layers), and aquifers (blue). From Major Hydrogeologic Units of the Long Island Aquifer - NYS Dept. of Environmental Conservation from

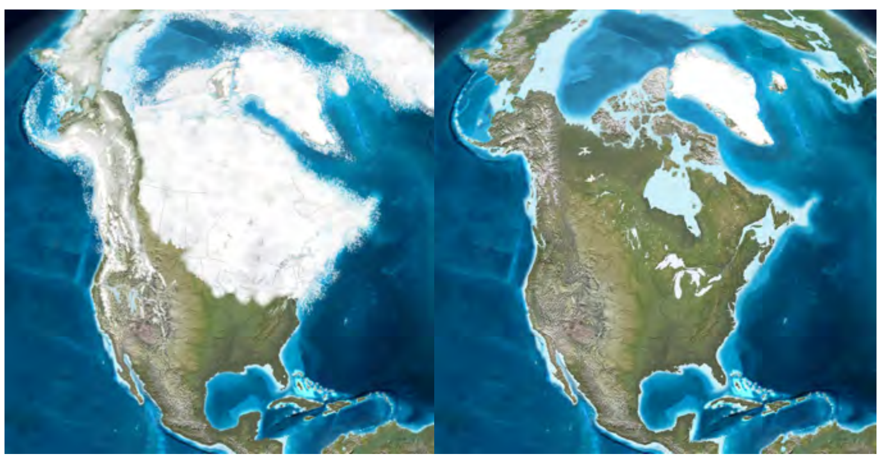


Figure 6. Continental glaciers (white) spread south as far as Long Island, NY, 100,000 years ago during the Pleistocene glaciation (left). Continental glacier cover today (right). By R. Blakley.

Overlying the Cretaceous sediments are unconsolidated sediments sourced from glaciers that traveled over the area starting about 100,000 years ago during the Pleistocene Ice Age. Large continental glaciers crept southward from the Arctic to the New York area (Fig. 6). The mile-thick ice traveled in a northwest to southeast direction (Fig. 7) and scoured the bedrock across New York City, producing many erosional features.

The glacier halted, stalled, and then retreated where Long Island is today, depositing mounds of glacial till ranging from clay particles to huge boulders and outwash (Fig. 8). Two moraines, or ridges of glacial rock, 1.6 to 3.2 kilometers (1 to 2 miles) in width and up to 100 meters (400 feet) elevation, were deposited along most of the length of the island: Ronkonkoma around 55,000 years ago and Harbor Hill around 18,000 years ago (Fig. 9).

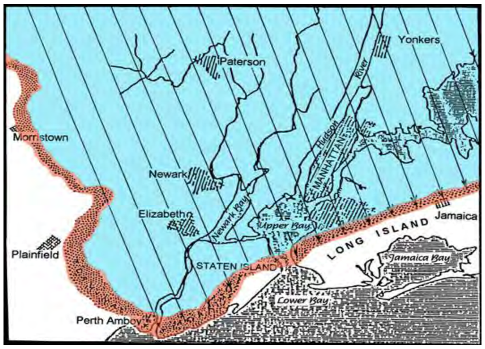


Figure 7. The glacier that terminated on Long Island flowed from NW to SE and deposited till and outwash. From Sanders & Merguerian (1994).

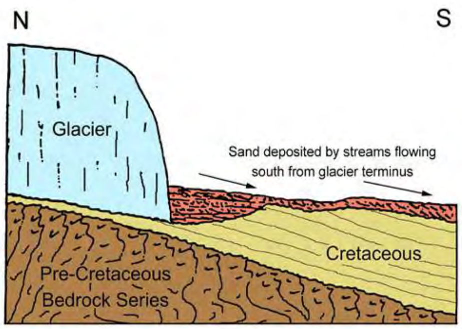


Figure 8. A cross-section from Connecticut (north) to Long Island (south) showing the terminus of continental glacier standing in what is now Long Island Sound and spreading sand and gravel southward to bury the Upper Cretaceous sediments and basement rocks. From Sanders & Merguerian (1994).

Both moraines run east to west along the spine of Long Island: The main highway, the Long Island Expressway, runs along the Ronkonkoma moraine, while Route 25A runs along the top of the Harbor Hill moraine on the north shore of Long Island (Fig 9). The moraines appear as hills, valleys, and kettle ponds. Sediment that washed out from under the ice as it melted formed outwash to the south the moraines. The relatively high elevation of Queensborough Community College indicates its location on the Harbor Hill moraine.

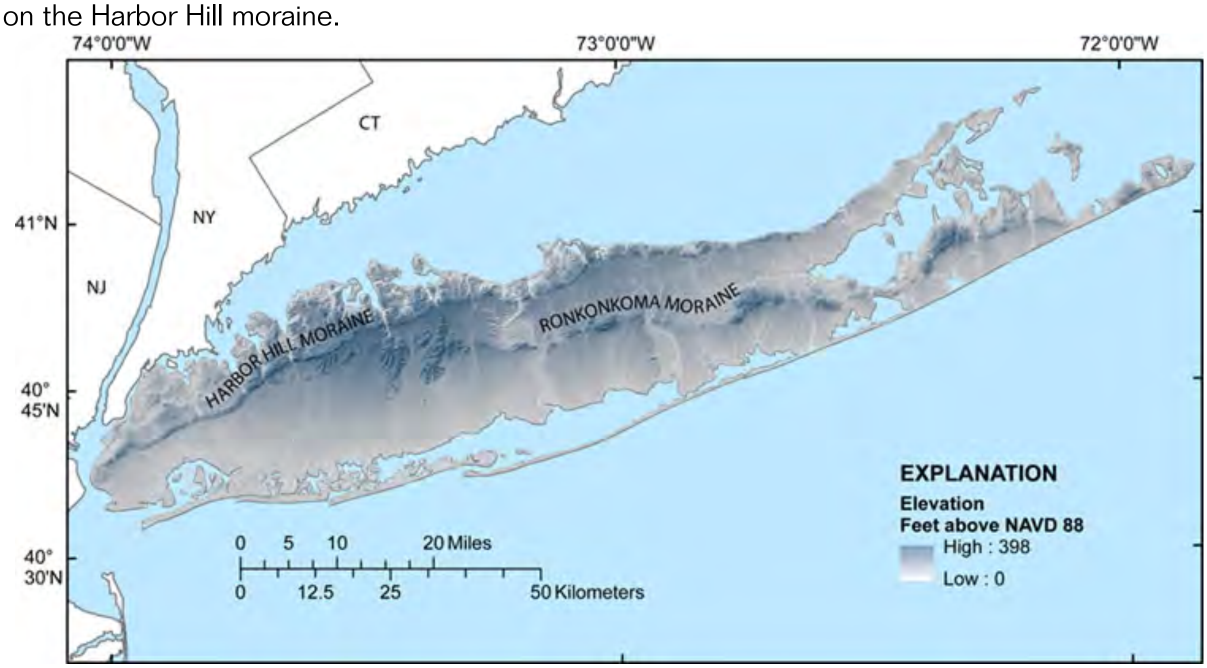


Figure 9. Topographic Map of Long Island showing the location of the moraines. From USGS

After glaciers deposited sediments that formed Long Island, the climate began to warm. About 18,000 years ago, the Wisconsinan ice sheet began to melt and retreat; it left the area about 10,000 years ago. The enormous quantity of water frozen into snow and ice during the Ice Age lowered sea level by about 120 meters worldwide. After the continental ice sheet melted, meltwater raised sea level again (Fig. 10).

Figure 10. Sea level (white line) was about 100 meters lower and extended farther offshore 18,000 years ago during the Pleistocene glaciation.

2. Newark Basin

The Triassic Newark and Hartford basins are situated between the Appalachian Mountains to the west and the Coastal Plain to the east and represents reddish shales, mudstones, and sandstones that stretches nearly 1,600 kilometers (1,000 miles) from the Hudson River near Nyack, New York, southward through Maryland and Virginia. The gentle rolling surface of sedimentary sandstones and shales are interrupted by ridges of erosion-resistant mafic igneous rocks such as the Watchung Mountain ranges of New Jersey, composed of extrusive basalts, and the Palisades Sill that lines the Hudson River north of Manhattan. These rocks formed about 200 million years ago.

3. Manhattan Prong

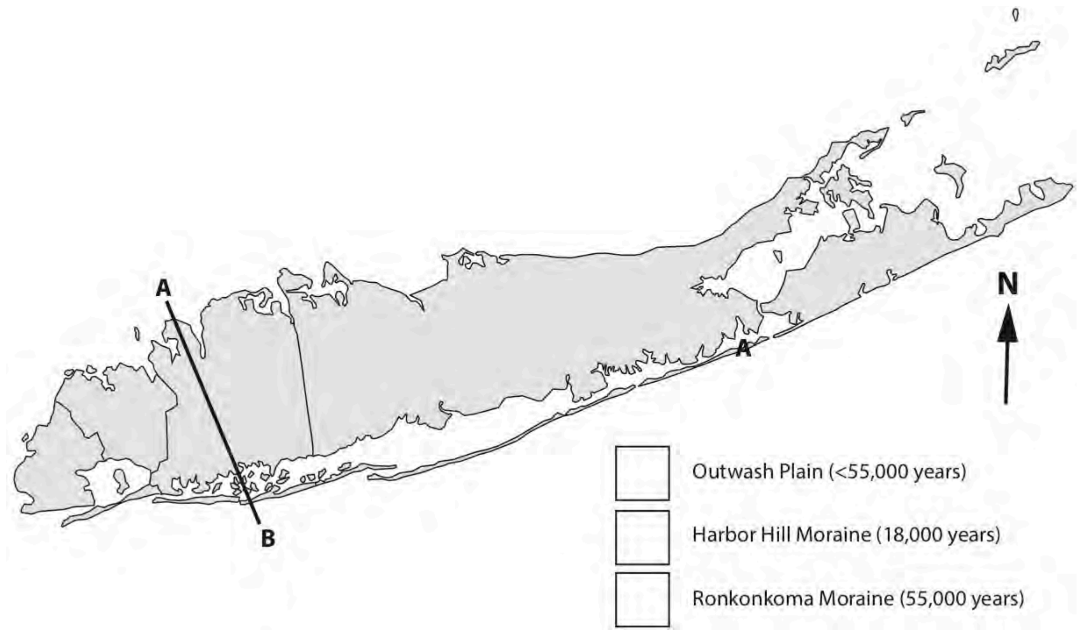
The *Manhattan Prong* consists primarily of metamorphic rocks (schist, gneiss, slate, and marble) and igneous rocks (largely granites and pegmatite) that have been greatly compressed, uplifted, and deeply eroded and rounded by glaciers. These rocks formed about 450 million years ago during the Taconic Orogeny plate collision. Just south of the Manhattan Prong, Staten Island is geologically distinctive in that it is partially underlain by serpentine rock, or serpentinite, an altered ultramafic igneous rock.

Part IV. Reading maps of Long Island – ELABORATE

Question 1.

Step 1: Referencing the DEM topographic map of Long Island (Fig. 9), use colored pencils to develop a legend for the elevated moraines (>400 ft elevation) on the map of Long Island in Figure 11.
Step 2: Using the colors from your legend, mark the rock units onto the map.
Step 3. Using Figure 12, draw a topographic profile between points A to B on the map.
Step 4. Take a photograph of your map and topographic profile and upload it in Blackboard.

Figure 11. Map and rock units of Long Island.



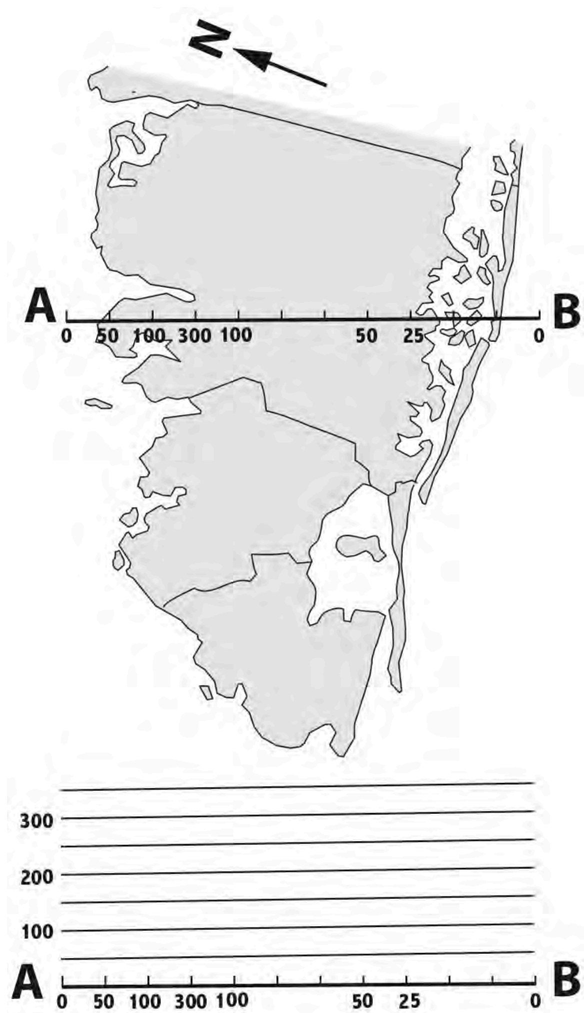


Figure 12. Topographic profile across Long Island between Point A and B. Elevation is in feet.

Question 2. Looking at the topographic map of Long Island (Fig. 9) can you tell which moraine formed first? (Hint: use the principle of cross-cutting relationships to inform your answer.)

A. The Ronkonkoma Moraine cross-cuts the Harbor Hill Moraine so it must be younger.
B. The Harbor Hill Moraine cross-cuts the Ronkonkoma Moraine so it must be younger.
C. Neither moraine cuts across the other so you cannot tell which moraine formed first.

Question 3. Watch the video showing the formation of Long Island and then briefly describe the glacial history of the area. https://www.youtube.com/watch?v=4UyocM9bDL4

Map Locations

Any point on the Earth's surface can be represented as an intersection of a line of latitude and a line of longitude. **Latitude lines,** or parallels, are parallel to the Equator and measure distances north and south of the Equator. **Longitude lines**, or meridians, pass through the North and South Poles (Fig. 13). Longitude lines measure distances east and west of the Prime Meridian, which passes through Greenwich, England. Since all of North America is north of the Equator and west of the Prime Meridian, all latitudes in the continental United States are north and all longitudes are west. Latitude and longitude are expressed in degrees, minutes, and seconds. 1 degree (°) = 60 minutes ('), 1 minute = 60 seconds ("). 360° makes a complete circle.

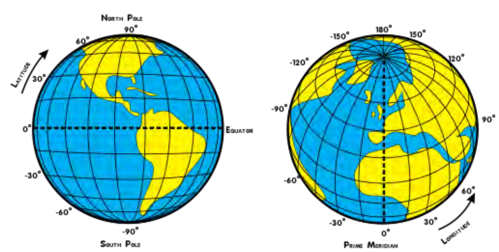


Figure 13. Lines of latitude and longitude on the globe.
From Djexplo - Own work.

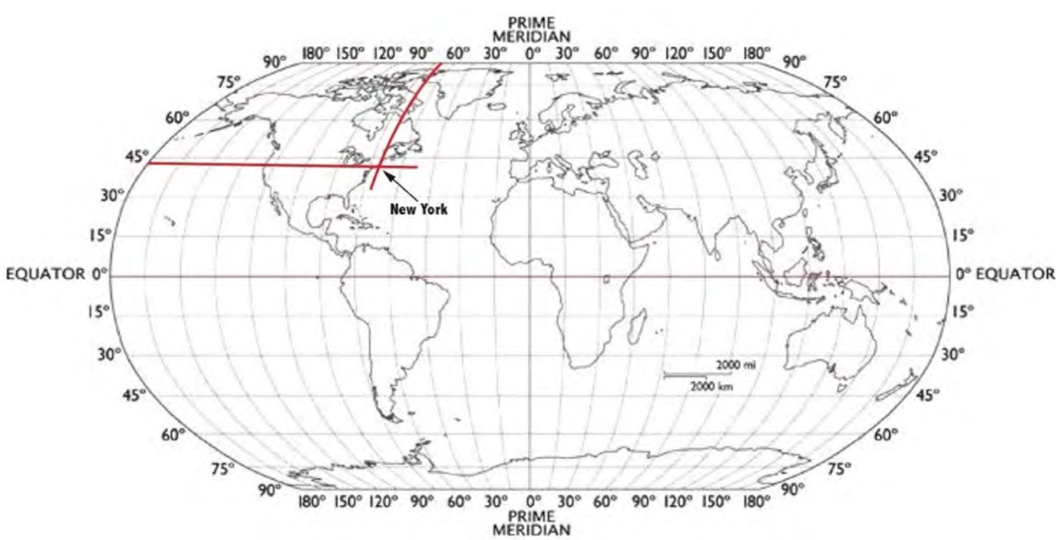


Figure 14. Lines of latitude and longitude on a world map. The prime meridian runs through Greenwich, England. Modified from Worldatlas.com

Question 4. What direction do latitude lines go?

A. North-South
B. West-East

Question 5. What direction do longitude lines go?

A. North-South
B. West-East

Question 6. Lines of latitude and longitude use a grid to help to locate exact places on the Earth.

A. True
B. False

Question 7. Use the world map (Fig. 14) determine the approximate the location of New York City. Determine the approximate latitude and longitude at this location.

Latitude:_____________________, Longitude:_____________________

Question 8. Locate the following glacial features on Long Island by searching in Google Maps. Provide the latitude and longitude of these features in Table 2. You can find definitions for glacial features in the appendix 1 at the back of the lab.

[Note: latitude and longitude can be found in the address bar of Google Maps. For example: the Statue of Liberty is located at: https://www.google.com/maps/@40.6894823,-74.0464256,17.53z where the latitude is 40.6894823 and the longitude is -74.0464256]

Table 2.

Glacial Feature	**Google Maps Search**	**Latitude**	**Longitude**
Erratic	Montgomery stone, Wading River		
Kettle Lake	Oakland Lake		
Harbor Hill Moraine	Queensborough Community College		

Part V. Coastal landforms of Long Island – EXPLORE 2

By the end of the Pleistocene 10,000 years ago, glaciers had deposited huge quantities of sediment along the shores of Long Island. Since then, the coastal sediments have been continually rearranged by wind and water currents.

Step 1. Go to the website "*Coastal Change at Fire Island*" https://wim.usgs.gov/geonarrative/ficc/
Step 2. Navigate to the tab titled "*Dynamic Coasts.*"
Step 3. In the left sidebar scroll down to "*Barrier Island Evolution.*" To the right, read the section "*How Barrier Islands Form and Evolve.*"

Question 1. At Fire Island, in what direction does longshore drift move sediment along a beach?

A. Perpendicular to the beach
B. Parallel to the beach
C. At an oblique angle to the beach

Step 4. Using the "*Coastal Change at Fire Island*" website, navigate to the tab titled "*Long Term Change.*"

Step 5. In the left sidebar scroll to read about how the western shoreline of Fire Island has changed rapidly through historical time. Observe the map in the right section to explore how the shoreline has changed between 1830 and 2007.

Question 2. Based on the changes to the western spit of Fire Island, what is the direction of longshore drift at this location?

A. North to south
B. South to north
C. East to west
D. West to east

Question 3. In 1830, the Fire Island Lighthouse was 0.5 miles from the end of the western spit of Fire Island. In 2022, the lighthouse is almost 5.5 miles or 8,700 meters from the end of the spit. Calculate the rate of spit growth between 1830 and today. [Rate = distance over time. The units are in meters per year.]

A. 15 meters/year
B. 30 meters/year
C. 45 meters/year
D. 60 meters/year

Part V. Coastal Landforms of Long Island – EXPLAIN 2

At the eastern end of Long Island, the erosion of glacial deposits at Montauk Point serves as the source of the beach sands that comprise the relatively recent (4,000 years) barrier island system from Southampton to Coney Island. Eroded glacial sediments are carried westward from Montauk Point in the coastal currents and deposited by wave action on beaches, building a series of barrier islands and spits along both shores of Long Island (Fig. 15). Fine sediments deposited in the bays behind the barrier islands form sand bars.

Figure 15. Coastal features at Jones Beach (top) and Lido Beach (bottom) separated by an inlet.
From Leo Chiou, CC BY-SA 4.0,

Spits: A spit is a ridge of sand that crosses the mouth of the bay part-way and forms when the longshore current carries sand across the mouth of a bay or estuary.

Barrier islands: A barrier island is a ridge made of sand, found parallel to the main coast with a lagoon or a bay separating the two.

Sand Bar: A submerged or partly exposed ridge of sand.

Due to the prevailing wind in the South Atlantic region, the dominant wave direction in the New York Bight is from the southeast (Fig. 16). Hurricanes during the summer and nor'easters during the winter are responsible for intense periods of sediment transport and beach erosion or accumulation. Longshore transport of sand by wave action shapes the Long Island shoreline (Fig. 17).

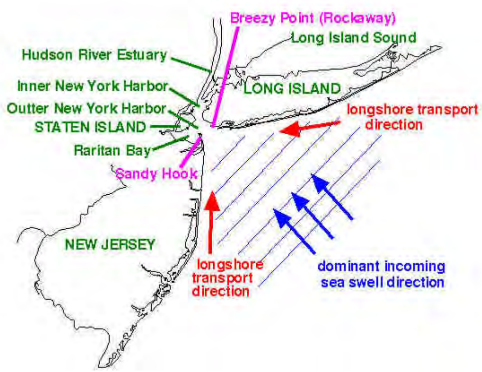


Figure 16. The dominant wave direction in the New York coastline is from the southeast due to prevailing wind zones and storm events in the South Atlantic region. This causes longshore currents from east to west along Long Island. From Stoffer, P., & Messina, P. (1996).

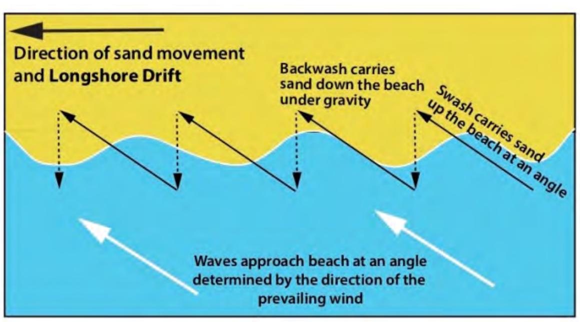


Figure 17. Longshore drift consists of the transportation of sand along a coast parallel to the shoreline due to an oblique incoming wave direction. Within the surf zone, breaking waves send water up the beach at an oblique angle. Gravity then drains the water straight downslope perpendicular to the shoreline. The beach sand moves down the beach in a sawtooth fashion tens of meters (yards) per day. The overall movement of sand is parallel to the coast.

On Long Island, the construction of long, narrow structures call groins and jetties built out into the water act like dams preventing longshore drift from washing sediment along the coast. As a result, they cause a buildup of sand on the side protected by the structure. But areas farther “downstream” on the coast are cut off from natural longshore drift by these barrier-like structures and experience worsened erosion (Fig 18).

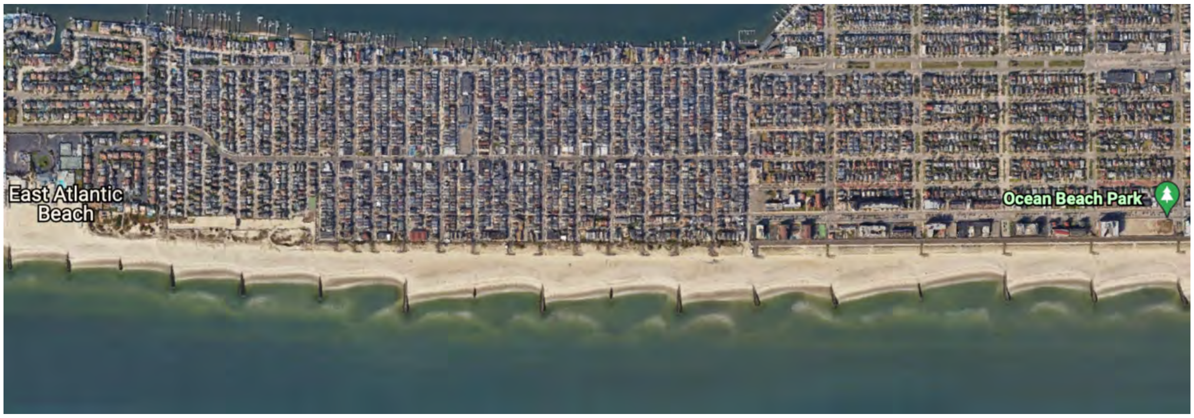


Figure 18. The building of groins and jetties along the beaches of Long Island help to trap sand moving with the longshore current. Sand builds up on the updrift side of the groin (right side of structures) and is eroded from the downdrift side of the groin (left side of structures). From Google Earth

Question 4. By 2100, sea levels are predicted to rise up to 6 feet in New York due to melting of polar ice caused by global warming. What would the impact of sea level rise on Long Island be?

A. Sea water would inundate many coastal communities.
B. There would be more flooding.
C. The entire Long Island coastline would move further inland than it is now, destroying many homes.
D. All of the above

Figure 19. In 2012, hurricane Sandy pushed sand inland and cut a channel through the eastern end of Fire Island. The channel is still open today.
From USGS

Question 5. In 2012, Hurricane Sandy reshaped beaches and dunes on Fire Island, pushing sand inland and cutting a channel through the eastern end at Otis Pike Fire Island High Dune Wilderness (Fig. 19). This breach has remained open since and is being closely monitored by the USGS and National Park Service. Some groups want to close the breach, while others want to let nature take its course and let the breach close on its own. Those in favor of closing the breach are worried about increased flooding on the south side of Long Island. Those in favor of keeping it open are finding the introduction of ocean water to the Great South Bay has improved water quality, which had degraded over time due to stormwater runoff, lawn chemicals, and septic leaks. Explore the information in the provided link below regarding closing the channel or allowing it stay open and then discuss your opinion on this debate: https://www.usgs.gov/news/featured-story/fire-island-wilderness-breach-help-or-hindrance

Part VI. Questions – EVALUATE

Question 1. Which of the five boroughs of New York City is an island?

A. Manhattan
B. Brooklyn
C. Queens
D. Bronx
E. Staten Island

Question 2. How old was the continental ice sheet when it first covered the New York area during the Pleistocene glaciation?

A. About 1000 years old
B. About 10,000 years old
C. About 100,000 years old
D. About 1,000,000 years old

Question 3. How did the continental ice sheet lead to the formation of Long Island?

A. The ice sheet traveled as far south as Long Island
B. The ice sheet deposited piles of rock, or moraines, where it terminated and began to retreat.
C. Both A and B

Question 4. On what rock formation is Queensborough Community College located?

A. Manhattan Prong
B. Ronkonkoma moraine
C. Harbor Hill moraine
D. Newark Basin

Question 5. Which one of the following has NOT been affected by glacial erosion or deposition?

A. The Finger Lakes, New York
B. The Mississippi River, Wisconsin
C. The Everglades, Florida
D. New York City

Question 6. What is the source of the rocks that makes up the moraines of Long Island?

A. Glacial erosion and transportation of rocks from southern New Jersey.
B. Glacial erosion and transportation of rocks from the north and northwest.
C. Erosion of glacial till at Montauk Point on the eastern tip of Long Island.
D. Sediments on the floor of the Long Island Sound washing onto land during storms.

Question 7. What is the source of the sediments that make up the beaches of Long Island?

A. Glacial erosion and transportation of rocks from southern New Jersey.
B. Glacial erosion and transportation of rocks from the north and northwest.
C. Erosion of glacial till at Montauk Point on the eastern tip of Long Island.
D. Sediments on the floor of the Long Island Sound washing onto land during storms.

Question 8. What coastal feature occurs on the eastern shoreline of Fire Island?

A. Sandbar
B. Barrier Island
C. Spit
D. Marsh

Sources

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Figure 9. Map of Long Island topography. Map of Long Island topography | U.S. Geological Survey. (n.d.). Retrieved January 7, 2022, from https://www.usgs.gov/media/images/map-long-island-topography

Figure 13. By Djexplo - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=15351129

Figure 14. Modified from Worldatlas.com

Figure 15. By Leo Chiou - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=51017746

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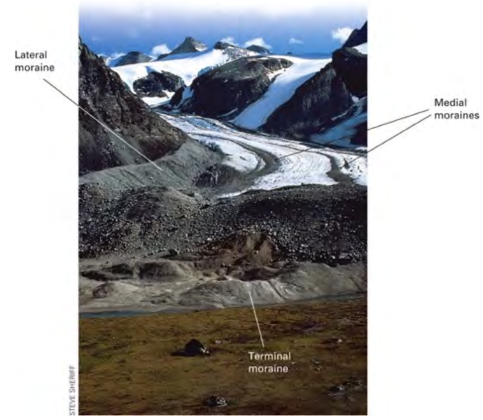
Appendix 1. Definitions of glacial features found on Long Island

[Image source: USGS]

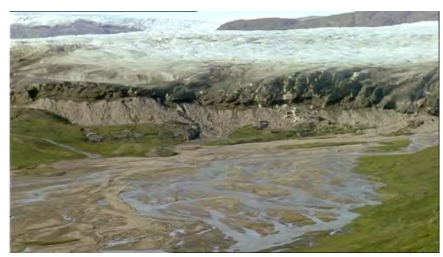
Moraine: A general term for unstratified and unsorted deposits of sediment that form through the direct action of, or contact with, glacier ice. Many different varieties are recognized on the basis of their position with respect to a glacier.



Terminus: The lower-most margin, end, or extremity of a glacier. Also called Toe, End, or Snout.

Till: An unsorted and unstratified accumulation of glacial sediment, deposited directly by glacier ice. Till is a mixture of different sized material deposited by moving ice or by the melting in-place of stagnant ice.

Outwash Plain: A broad plain composed of glacially eroded, sorted sediment (termed "outwash") that has been transported by glacial meltwater. The plain begins at the foot of a glacier and may extend for miles.



Erratic: A rock transported a significant distance from its origin by a glacier and deposited by melting of the ice. Erratics range from pebble-size to larger than a house and usually are of a different composition that the bedrock or sediment on which they are deposited.

Kettles: A bowl-shaped depression in glacial sediment filled by a lake or swamp. Kettles form by the melting of large, detached blocks of ice left behind by a retreating glacier.

11.1 How is climate changing?

How is sea level rise impacting New York City?

Purpose

The purpose of this lab is to become familiar with data used to determine changes in climate, both present and past, and what these changes mean for the future. Students will observe and interpret images and graphs depicting current and past climate data and find evidence for rapid changes to climate today resulting from human activities.

Learning objectives

After doing this lab you will be able to:

1. Discuss sea level changes in New York.
2. Explain that gravity satellite data is recording a decline in ice cover over Greenland and the implications for sea level rise.
3. Explain how atmospheric carbon dioxide or CO_2 and temperature are interconnected; increases in CO_2 over time lead to increases in temperature.
4. Explain how climate warming and cooling is a natural process.
5. Explain that the rates of warming today are rapid and accelerating compared to the past.
6. Explain that humans are the cause for warming today.

Part I. How is sea level rise impacting New York City? – ENGAGE

Temperatures change all the time. Over the course of a year, we see gradual increases in daily and monthly average temperatures, as winter eases into spring and summer, and watch them fall again as summer turns to autumn and then back to winter. When we look at temperature on a regional or global scale over the course of many years, climatic patterns emerge.

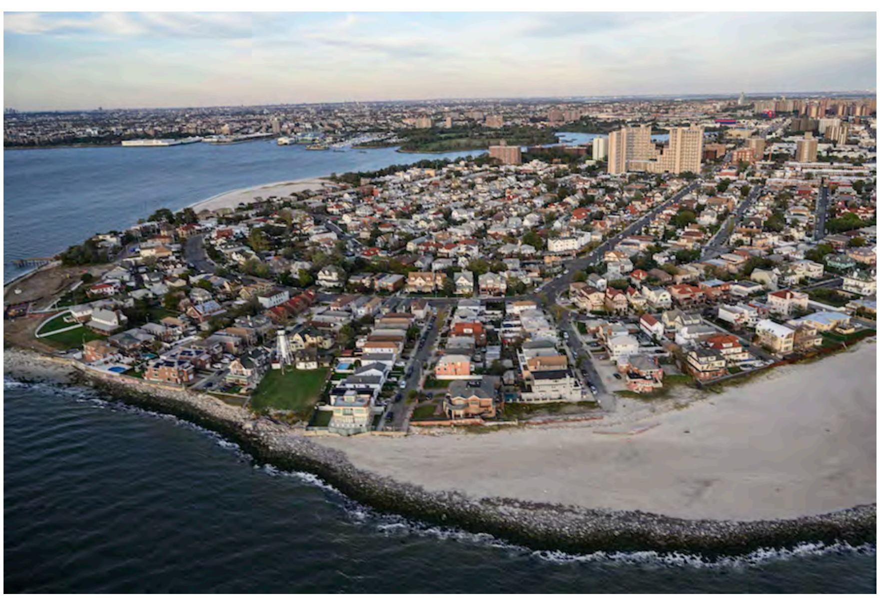


Figure. 1. With houses built right on the coastline, the Rockaways were hit hard by superstorm Sandy in 2012 and are still vulnerable. From van Lohuizen, K. (2018). Rising sea levels and New York City.

Question 1. Look at Figure 1. What do you see? Is there anything protecting the buildings from the water?

Question 2. Due to climate change, scientists predict that sea level in New York City will rise by up to six feet by 2100. If the water levels continue to rise, what do you think would happen to this neighborhood?

Question 3. What other affects will sea level rise have on New York City?

Question 4. What are some ways we could help protect this neighborhood from rising water levels?

Part II. Sea level changes in Greenland – EXPLORE

GRACE: Tracking Water from Space

Step 1. Watch the video - GRACE: Tracking Water from Space: https://www.youtube.com/watch?v=Vus2XM-3q4A

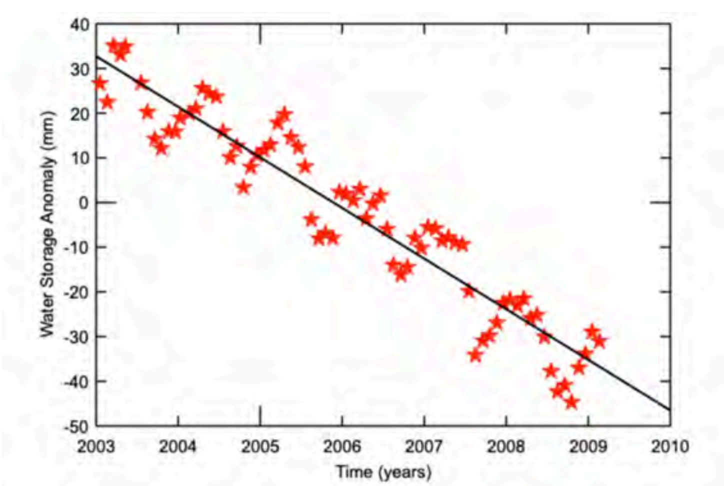


Figure 2. Greenland GRACE satellite data mapping water and ice storage anomalies or changes between 2003 and 2009. The red stars record ice storage data for each month. The black is an average of the data showing a trend or pattern of change. Data from NASA

Step 2. Answer the following questions based on Figure 2 Greenland GRACE water storage anomaly data.

Question 1. How much did the water storage change between 2003 and 2009?

A. Water storage decreased and then increased.
B. Water storage increased by 80 mm.
C. Water storage decreased by 80 mm.
D. Water storage stayed the same

Question 2. Is there a trend (or pattern of gradual change) in the water storage data? If so, what do you think this trend is representing regarding the water and ice storage anomaly over the six-year period?

A. Water storage has been increasing over the six year period.
B. Water storage has been decreasing over the six year period.
C. Water storage has remained the same over the six year period.

Question 3. As you look at the Greenland water storage data over time, besides the long-term linear pattern, are there any seasonal patterns that you observe?

A. Water storage decreases in winter and increases in summer.
B. Water storage increases in winter and decreases in summer.
C. There is no change in water storage between the winter and summer seasons.

Question 4. Does this data have any implications for sea level rise in New York?

A. Increasing ice storage is causing sea level to rise.
B. Increasing ice storage is causing sea level to fall.
C. Decreasing ice storage is causing sea level to rise.

Part III. Carbon Dioxide (CO_2) vs. Temperature – EXPLAIN

Step 1. Your instructor will provide a short introduction to the greenhouse effect. Alternatively, watch this video about the greenhouse effect from National Geographic: https://www.nationalgeographic.com/environment/global-warming/greenhouse-gases/

Question 1. Circle any of the following compounds that are greenhouse gases.

A. Water vapor (H_2O) E. Methane (CH_4)
B. Oxygen gas (O_2) F. Nitrous oxide (N_2O)
C. Nitrogen gas (N_2) G. Ozone (O_3)
D. Carbon dioxide (CO_2) H. Chlorofluorocarbons (CFCs)

Question 2. Describe what the greenhouse effect is.

A. A phenomenon related to planting a garden in a greenhouse.
B. The upper atmosphere near space traps greenhouse gases causing the planet to warm.
C. The Sun is getting hotter causing the Earth to warm.
D. Greenhouse gases in the lower atmosphere trap heat from outgoing solar radiation causing the atmosphere to warm.

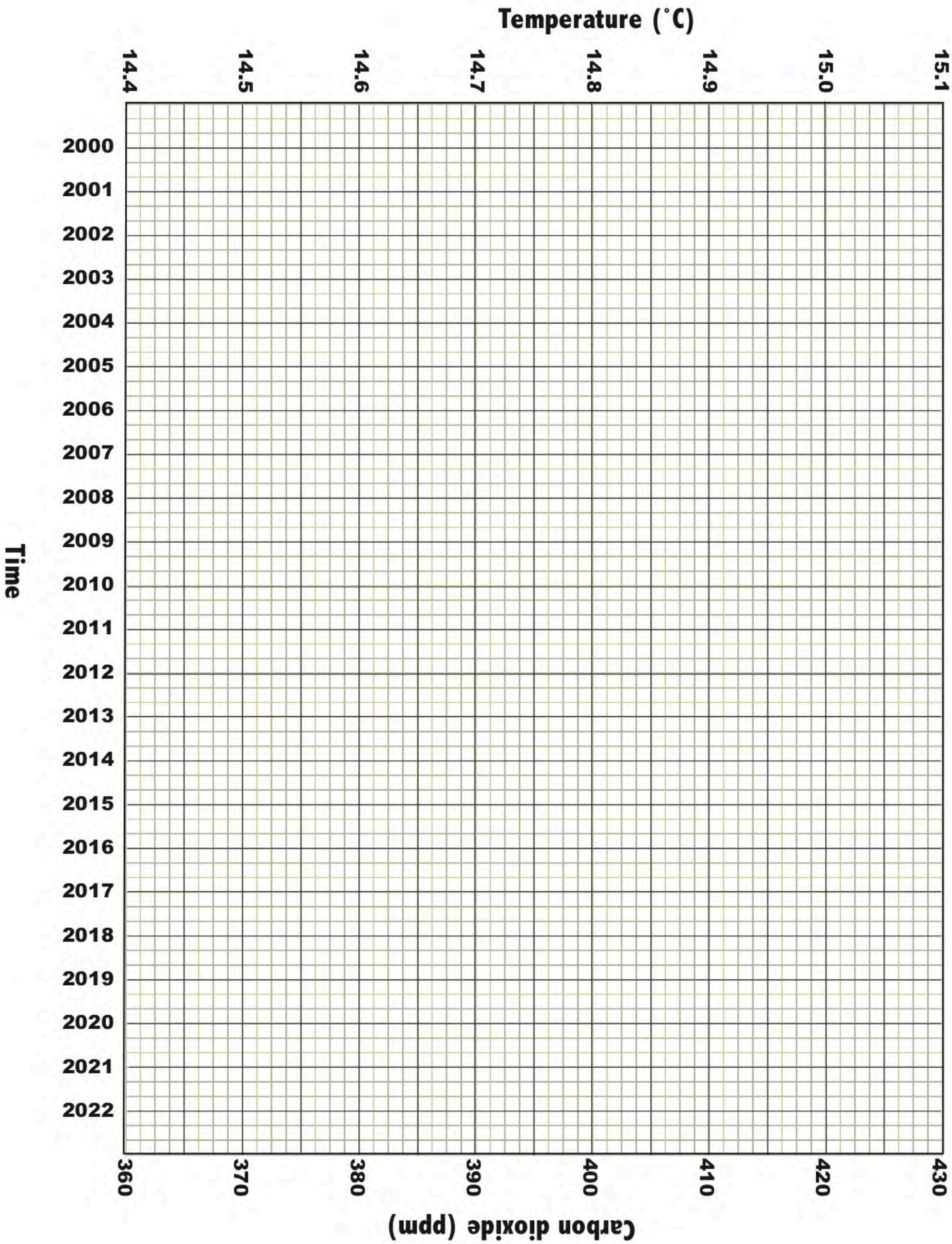
Plotting Temperature and Carbon Dioxide Data
In this section you will graph average annual global temperatures and average atmospheric carbon dioxide measurements from 2000 to 2020 versus time. Atmospheric CO_2 is measured at Mauna Loa Observatory, Hawaii. Global annual temperature is measured at locations around the globe and is a measure of how much the Earth has warmed relative to 1951-1980 average temperatures.

Question 3. Plot temperature and carbon dioxide data from Table 1 onto the provided graph paper (Figure 3). Use different colors for each variable.

Table 1. Average global temperature and carbon dioxide data.

Year	Temperature (°C)	CO_2 (ppm)
2000	14.5	369.7
2001	14.5	371.3
2002	14.5	373.5
2003	14.6	376
2004	14.6	377.7
2005	14.6	380
2006	14.6	382.1
2007	14.6	384
2008	14.6	385.8
2009	14.6	387.6
2010	14.6	390.1
2011	14.7	391.9
2012	14.7	394.1
2013	14.7	396.7
2014	14.7	398.9
2015	14.8	401
2016	14.8	404.4
2017	14.9	406.8
2018	14.9	408.7
2019	14.9	411.7
2020	14.9	414.2
2021	14.9	416.6
2022		

Figure 3. Time versus Temperature and Carbon Dioxide



Looking at your plot of time versus temperature and carbon dioxide (Fig. 3), answer the following questions.

Question 4. Between 2000 and 2020, how has the average global temperature changed? (Quantify your answer using degrees centigrade.)

Question 5. Between 2000 and 2020, how has average global atmospheric carbon dioxide values changed? (quantify your answer using parts per million or ppm).

Question 6. Calculate the rate of change of temperature and carbon dioxide values in the 20-year time interval. Rate is temperature/time in °C/year and CO_2 ppm/year.

Rate of change in temperature: __________ °C/year

Rate of change in CO_2: _____________ ppm/year

Question 7. Based on your graph, describe how the variables temperature and carbon dioxide change with respect to one another over time?

Part IV. Temperature and atmospheric CO_2 concentrations from the ice core record – ELABORATE

If climate is changing today, has it also changed in the past? Are the changes we are seeing normal? To find out we must look into the climate record from the past. The term "ice age" or glacial age describes any geological period in which long-term cooling takes place and ice sheets and glaciers exist. That means we are currently in the midst of an ice age right now! More specifically, we are in an **interglacial** (warm period) within a glacial age. Cold periods within a glacial age are called **glacials** or **glaciations** and are characterized by cooler temperatures and advancing glaciers.

Ice cores have been taken from many locations around the world, primarily in Greenland and Antarctica. One of the deepest cores ever drilled in Antarctica includes ice from as far back as 800,000 years ago.

Step 1. Watch this video about scientists in the Antarctica extracting ice cores from the continental glacier to learn about how the data in Figure 4 was collected.
Link: https://www.youtube.com/watch?v=VjTsj-fi-p0

Step 2. In Part III, you plotted Temperature and CO_2 concentrations over time. In this section you will be analyzing the same kind of data over 800,000 years. Examine the plot of EPICA ice core data collected in Antarctica (Fig. 4). The x-axis shows age, so an age of 0 represents something happening today, and an age of 800,000 represents something that happened 800,000 years ago. Note "ppmv" stands for parts per million by volume. The temperature values are based on an average temperature close to the present. Negative temperature values are below average, and positive values are above average. As you move from right to the left along the x-axis, you are essentially looking back in time. This data shows a strong connection between CO_2 concentrations in our atmosphere and temperature. Working together with your lab partner(s), answer the following questions about Figure 4.

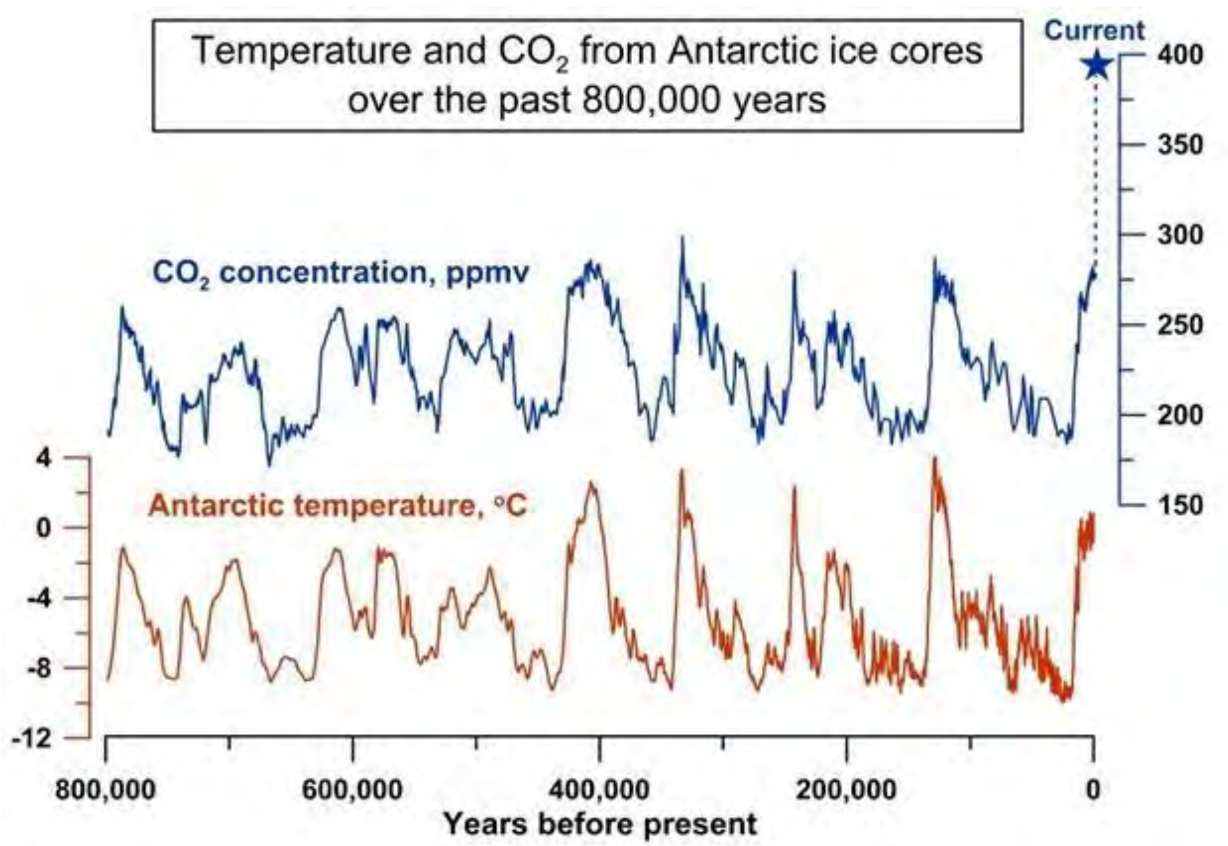


Figure 4. Temperature change (red) and carbon dioxide change (dark blue) over the past 800,000 years. Note that temperature values are measured from hydrogen isotope ratios in the ice and are calculated based on an average temperature close to the present. Negative temperature values are below average and positive values are above average. From Bailey et al. (2015).

Question 1. In the 800,000 year ice core data (Fig. 4), compare the patterns of temperature and atmospheric carbon dioxide data. What does this indicate about the relationship between temperature and carbon dioxide?

Question 2. Use Figure 4 to determine the highest and lowest temperature value recorded in the Antarctic ice over the past 800,000 years?

Highest temperature:_____________˚C, Lowest temperature: _______________˚C.

Question 3. Use Figure 4 to determine the highest and lowest carbon dioxide value recorded in the Antarctic ice over the past 800,000 years.

Highest carbon dioxide value:_______ ppm, Lowest carbon dioxide value:_______ ppm.

Question 4. In Figure 4, measure the temperature and carbon dioxide content of the atmosphere at about 150,000 years ago during a glacial (colder) cycle. Secondly, measure the temperature and carbon dioxide content of the atmosphere at about 110,000 years ago during an interglacial (warmer) cycle. Finally, calculate the rate that carbon dioxide and temperature increased over the 40,000 year time interval between 150,000 and 110,000 years ago.

Variable	**150,000 years ago**	**110,000 years ago**	**Rate of change (difference/time)**
Temperature			
Carbon dioxide			

Question 5. Compare the rates of change in carbon dioxide and temperature in Question 4 (above) to the 2000-2020 time period in Part III.

Rate	**150,000 to 110,000 years ago**	**2000-2020**
Rate of change of temperature (˚C/year)	˚C/year	˚C/year
Rate of change of carbon dioxide (ppm/year)	ppm/year	ppm/year

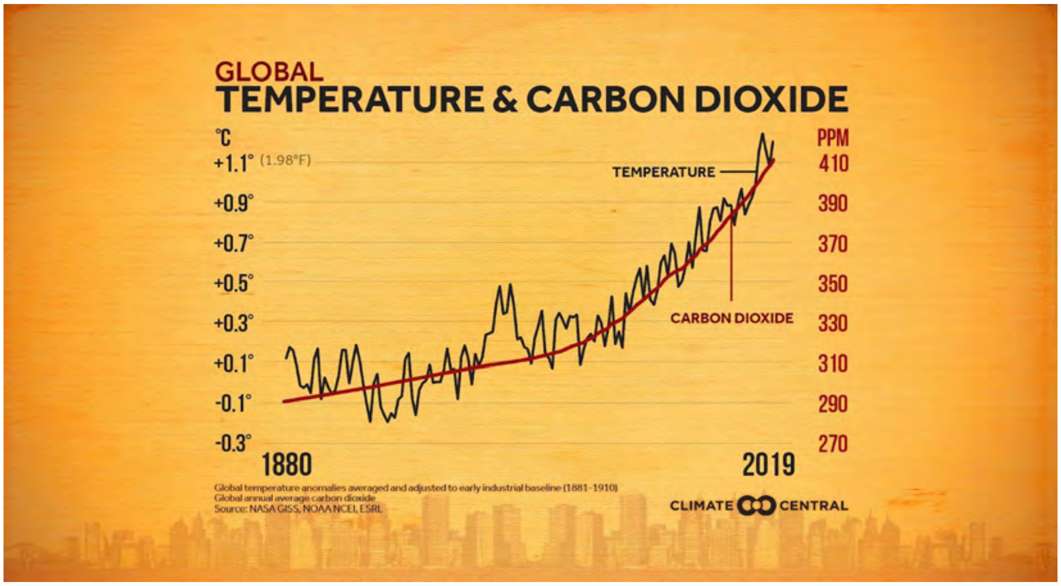


Figure 5. Global annual temperature given as temperature anomalies based on an average global temperature between 1880 and 1910 (black) and carbon dioxide concentrations since 1880 (red). From Climate Central.

Question 6. Figure 5 shows the change in average global temperature and carbon dioxide in the past 140 years since 1880. What is driving this change?

Question 7. What else might lead to changes in temperature over time? How could you test if there is a relationship?

V. Questions — EVALUATE

Question 1. Which is correct about how New York is vulnerable to flood risks from sea level rise?

A. Sea level could rise six feet by 2070.
B. Sea level rise causes higher risk of flooding of coastal communities.
C. Sea level rise causes damage to the city's infrastructure such as subway tunnels, power plants, and buildings.
D. All of the above.

Question 2. Today's rising greenhouse gas levels are caused by:

A. Burning fossil fuels such as coal, oil, and gas for energy and transportation.
B. Deforestation of natural forests.
C. Cement production.
D. All of the above.

Question 3. Today the Greenland ice storage is decreasing. This is because of:

A. Climate cooling.
B. Climate warming.
C. No effect.

Question 4. The melting of the Greenland polar ice will result in:

A. An increase in ice cover over the polar regions.
B. Sea level rise.
C. Sea level fall.
D. No effect.

Question 5. The temperature record from the EPICA ice core in Antarctica goes back more than:

A. 800 years.
B. 800 thousand years.
C. 800 million years.
D. 800 billion years.

Question 6. Since about 1880 the amount of greenhouse gases in the atmosphere, such as carbon dioxide (CO_2), directly corresponds to:

A. Climate cooling.
B. Climate warming.
C. There is no correlation between these variables.

Question 7. The EPICA ice record shows a cycle of warming and cooling through time. Increases in temperature correspond to:

A. Increases in atmospheric carbon dioxide (CO_2).
B. Decreases in atmospheric carbon dioxide (CO_2).
C. There is no correlation between these variables.

Question 8. The highest CO_2 value in the EPICA ice core is about 295 ppm, while the highest CO_2 value in recent time (2021) is 417 ppm. What is the cause of this recent 122 ppm increase in atmospheric CO_2?

A. The increase in CO_2 values is part of the natural cycle of warming and cooling.
B. CO_2 levels have increased due humans burning fossil fuels.
C. CO_2 levels have decreased due humans burning fossil fuels.

Exercise sources

Part III. Carbon Dioxide (CO_2) vs. Temperature and Part IV. Temperature & atmospheric CO_2 concentrations from the ice core record are adapted from Climate Change: Past & Present, Local & Global. Activities. (2021, August 31).

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Climate Change: Past & Present, Local & Global. Activities. (2021, August 31). https://serc.carleton.edu/inquiry_intro_geo/activities/244907.html

Figure sources

Figure. 1. van Lohuizen, K. (2018). Rising sea levels and New York City. Museum of the City of New York. (n.d.). Retrieved January 8, 2022, from https://www.mcny.org/education/rising-sea-levels-and-new-york-city

Figure 4. From Bailey et al. (2015).

Figure 5. Global temperatures and CO_2 concentrations (2020). Climate Central. (2020, February 19). Retrieved January 8, 2022, from https://www.climatecentral.org/gallery/graphics/global-temperatures-and-co2-concentrations-2020

11.2 How is climate changing?

Climate change science videos

Watch the four climate change videos and answer the following questions.

Video 1. Scientists at Work: Greenland Ice Core (start at 4 minutes)
Link: http://vimeo.com/59680684

1. In what way are ice cores a time machine?

2. How far back in time does the Greenland ice core go?

3. How can you see annual layers in the ice core?

4. Why are ice cores so important in the study of paleoclimate (past climate)?

Video 2. Watch Shrinking Glaciers
Link: http://vimeo.com/60198340

1. Why is it important to date glacier movement in the past?

2. What are some of the findings of this study?

Video 3. Archived in Ice
Link: http://vimeo.com/60198337

1. At what locations are these scientists studying ice?

2. Where do tropical glaciers occur?

3. How old is the plant exposed by the retreating glacier? What is significant about this age?

Video 4. Ocean Acidification

Link: http://vimeo.com/53685081

1. What are the sea urchins used to study?

2. What is ocean acidification? (pH is acidity)

3. How has the sea urchin larvae growth changed with changes to pH or ocean acidity?

12.1 AMNH Hall of Planet Earth Field Trip

Address: Central Park West at 79th St, New York, NY 10024
Opening hours: 10 AM to 5:45 PM Wednesday to Sunday
Subways: B or C to 81Street Station
At the museum: Upon entry, purchase a ticket, pick up a floor plan, and head to the Hall of Planet Earth on the First Floor.

The Hall of Planet Earth is divided into five organizing questions (see locations on map below):

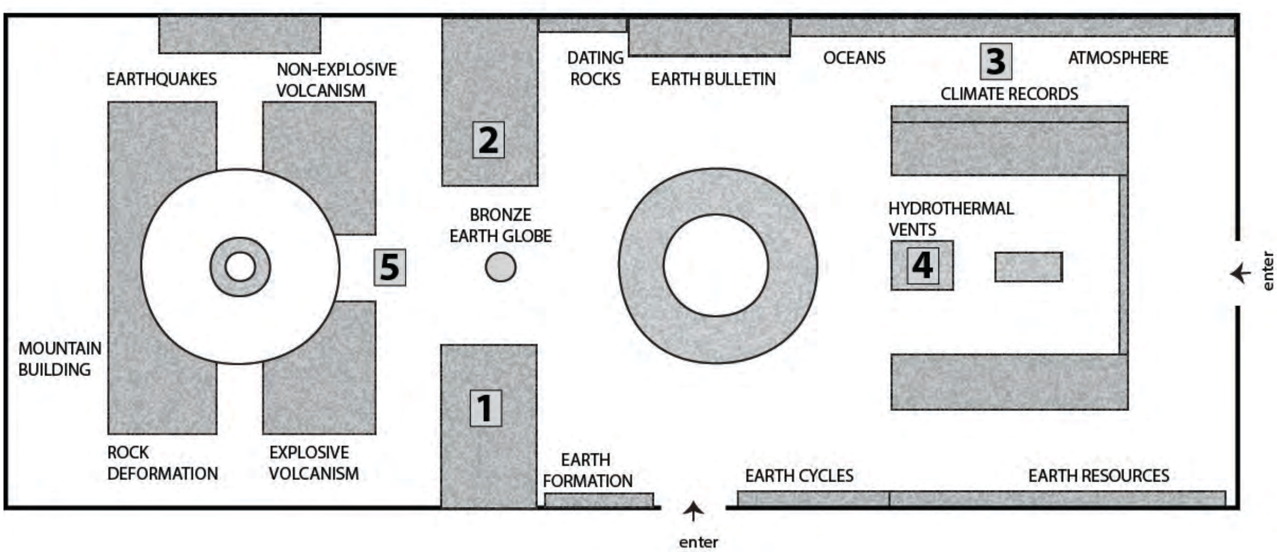
1 How has the Earth Evolved?

2 How do we Read the Rocks?

3 What Causes Climate and Climate Change?

4 Why is the Earth Habitable?

5 Why are there Ocean Basins, Continents, and Mountains?



This Field Trip is also divided into five parts based on the five organizing questions. **Choose three of the five parts of the worksheet to complete on your visit. Also complete the final question on the last page of the packet.** The three sections and final question should take one hour to complete.

As proof of your visit be sure to keep your entry ticket and take a short video of yourself at the exhibit, which you can show to your instructor.

1 How has the Earth Evolved?

HOW DID THE EARTH FORM?

a. List and describe the six stages that led to the formation of Earth.

1. Nebular stage	Gravity caused collapse of a rotating mass of dust and gas.
2. A star forms	
3. Planetesimals form	
4. The Sun ignites	
5. Inner planets	
6. Outer planets	

OLDEST ROCK AND MINERALS ON EARTH. SPECIMEN #12, ACASTA GNEISS

b. How old is this rock, and how was its age measured?

A SPECIAL PLANET, HOW DO WE KNOW ABOUT THE EARTH'S EARLY ATMOSPHERE?

Specimen #14, stromatolite

c. What are stromatolites?

d. What environments do stromatolites form in?

e. During what time in Earth's history were stromatolites most extensive?

1 How has the Earth Evolved?

A SPECIAL PLANET, HOW DO WE KNOW ABOUT THE EARTH'S EARLY ATMOSPHERE?

Specimen #15, banded iron (also see #23 around the corner)

f. What are the bands in this rock made of?

g. Describe how the bands in this rock formed.

h. What does the presence of banded iron formations tell us about conditions in the early atmosphere and oceans?

2 How do we Read the Rocks?

THE FATHER OF GEOLOGY

a. What was the evidence that led James Hutton to propose the Earth was much older than originally thought?

b. Sketch the large wall model of Siccar Point and label the unconformity. What is the significance of the rocks James Hutton observed at this location?

THE PRESENT IN THE KEY TO THE PAST

c. How do specimens #1, #2, and #3 support the principle of uniformitarianism?

What is the meaning of the principle "The present is the key to the past"?	
1. Cross-bedded sandstone	
2. Ripple marks in sandstone	
3. Dike in granite	

2 How do we Read the Rocks?

DECIPHERING THE GRAND CANYON, BULIDING THE CANYON'S LAYERS

d.

What are the oldest group of rocks in the Grand Canyon, and what is their age?	
What are the youngest group of rocks in the Grand Canyon, and what is their age?	
What is the Great Unconformity?	

The Sea Retreats, The Sea Returns

e.

What two environments did the upper rock layers of the Grand Canyon form in?	
What conditions was the Coconino sandstone deposited in?	
What conditions was the Kaibab limestone deposited in?	

3 What Causes Climate and Climate Change?

WHY STUDY PAST CLIMATE?

a. Why do scientists study past climates?

b. What does the sediment core from Walvis Ridge, southern Atlantic Ocean, from 55–56 million years ago tell us about past climate?

WHAT ICE CORES RECORD

c. How far back in time does the Greenland ice core go?

d. List three things that can be measured from annual layers of ice cores.

1.	
2.	
3.	

3 What Causes Climate and Climate Change?

CONSEQUENCES OF CLIMATE CHANGE, WARMING WORLD, HOW CLIMATE WORKS

e. How is climate changing today?

f. What is driving climate change today?

g. What are some consequences of climate change?

4 Why is the Earth Habitable?

THE LIVING PLANET

a. Earth supports life because it meets a few vital conditions. List three of these conditions and explain.

1.	
2.	
3.	

SULFIDE CHIMNEYS FROM JUAN DE FUCA RIDGE

b. Where is the Juan de Fuca Ridge?

c. What are these sulfide chimneys made of?

d. What remains are preserved on the surface of the chimneys?

4 Why is the Earth Habitable?

LIFE AT THE HYDROTHERMAL VENTS

e. Scientists theorize that life begin at deep-sea vents. Find three lines of evidence to support this claim.

1	
2	
3	

f. Explain how sulfide chimneys can support life without the presence of sunlight.

5 Why are there Ocean Basins, Continents, and Mountains?

EFFUSIVE VOLCANISM, VOLCANOES UNDER THE SEA, & FLOOD BASALTS

a. For the following rocks, discuss how the cooling textures formed.

Rock no.	Rock name	Location where found	Cooling texture
#15			
#18			

EXPLOSIVE VOLCANISM

b. Observe the volcanic rocks from Medicine Lake volcano, California, that formed from magmas above a subduction zone. List the rock number, rock name, and cooling texture for three rocks.

Rock no.	**Rock name**	**Cooling texture**

HOW ROCKS DEFORM, DEFORMING ROCKS IN THE LAB, DEFORMING MARBLE (#8)

c. Describe how the marble cylinders changed when exposed to high temperatures of about 400˚C and different confining pressures.

Confining pressure	**Depth equivalent**	**Deformation style**	**Description of changes to cylinder and why**
203 atm		Brittle	
507 atm		Brittle	
2026 atm		Plastic	

5 Why are there Ocean Basins, Continents, and Mountains?

HOW ROCKS DEFORM, DEFORMED ROCKS, DEFORMED CONGLOMERATES (#6, 7)

d. How did this rock form?

e. What happens to the pebbles in the rock during deformation?

EARTHQUAKES, WHAT IS A FAULT? FAULTS IN CRYSTALLINE ROCK (ROCK #1)

f. Sketch the fault and the layers of rock that are displaced in rock #1.

Is this a normal or thrust fault?	
Did this rock experience compressional →←or extensional ←→ stress based on the fault type?	

FINAL QUESTION
Choose a rock, interactive, video, or exhibit that you find interesting.

a. Make a sketch of your selection

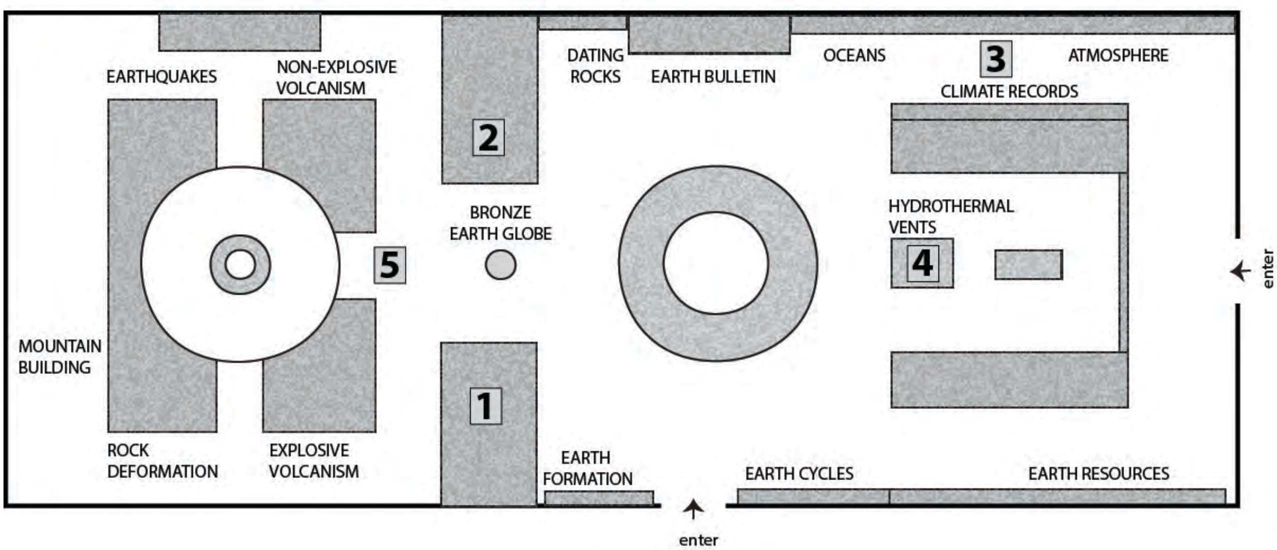
b. What about this rock, interactive, video, or exhibit is significant or interesting to you?

12.2 AMNH Hall of Planet Earth Field Trip (online)

Visit the Hall of Planet Earth online:
https://www.amnh.org/exhibitions/permanent/planet-earth

The Hall of Planet Earth is divided into five organizing questions (see locations on map below):

1. How has the Earth Evolved?
2. How do we Read the Rocks?
3. What Causes Climate and Climate Change?
4. Why is the Earth Habitable?
5. Why are there Ocean Basins, Continents, and Mountains?



This Field Trip is also divided into five parts based on the five questions. **Choose three of the five sections of the worksheet to complete on your online visit. Also complete the final question in this document. Each section is made up of about five questions.** The three sections and final question should take one hour to complete.

QUESTIONS

1 How Has the Earth Evolved? What We Learn From Meteorites. What does the Allende meteorite tell us about the formation of the Earth?

2 How Has the Earth Evolved? Ancient Sediments from Greenland. What do the Isua rocks tell geologists about the early Earth?

3 How Has the Earth Evolved? The Earth's Crust. The Oldest Rocks and Minerals on Earth. Why is zircon such an important mineral for studies of the Earth?

4 How Has the Earth Evolved? Banded Iron Formation. What are banded iron formations made of? What do BIF's tell us about Earth's early atmosphere?

5 How Has the Earth Evolved? A Special Planet. How do we know about the early atmosphere? What are stromatolites? What role did they play in oxygenating the atmosphere?

6 How Do We Read the Rocks? The Present Is the Key to the Past. How does the Cross-Bedded Sandstone support the principle of uniformitarianism?

7 How Do We Read the Rocks? The Present Is the Key to the Past. What was the evidence that led James Hutton to propose the Earth was much older than originally thought?

8 How Do We Read the Rocks? The Present Is the Key to the Past. Deciphering the Grand Canyon. What is the oldest rock unit of the Grand Canyon? How old are these rocks?

9 How Do We Read the Rocks? The Present Is the Key to the Past. Deciphering the Grand Canyon. What is the youngest rock unit of the Grand Canyon? How old are these rocks?

10 How Do We Read the Rocks? The Present Is the Key to the Past. Deciphering the Grand Canyon. What sedimentary environments did the Coconino Sandstone and Kaibab Limestone form in?

11 What Causes Climate and Climate Change? How Climate Works. Components of the Climate System. What are the five components of the climate system?

12 What Causes Climate and Climate Change? How Climate Works. Components of the Climate System. How Does the Ocean Control Climate? How are humans changing the carbon cycle?

13 What Causes Climate and Climate Change? Our Warming World. Causes of Global Warming. What ways are humans driving global warming?

14 What Causes Climate and Climate Change? Consequences of Warming. Climate Change and Risk. What are some of the risks of climate change? What are some things we can do to reduce the risks of climate change?

15 What Causes Climate and Climate Chang? What Ice Cores Record. How far back in time does the Greenland ice core go? Why do we study the ice record?

16 Why is the Earth habitable? Life that lives off the Earth's energy. Sulfide chimneys from the Juan de Fuca Ridge. Where is the Juan de Fuca Ridge?

17 Why is the Earth habitable? Life that lives off the Earth's energy. Sulfide chimneys from the Juan de Fuca Ridge. What is Godzilla? How did this structure form?

18 Why is the Earth habitable? Life that lives off the Earth's energy. Explain how sulfide chimneys can support life without the presence of sunlight?

19 Why is the Earth habitable? Where do the Earth's riches come from? Rare minerals from pegmatites. How do rare ore minerals concentrate in pegmatites?

20 Why are there ocean basins, continents, and mountains? Wallace Gilroy Bronze Earth model. What percentage of the crust is oceanic and what percentage is continental?

21 Why are there ocean basins, continents, and mountains? Explosive volcanism. Volcanic Bombs. What is a volcanic bomb? List the many types.

22 Why are there ocean basins, continents, and mountains? Medicine Lake volcano. Name some of the rocks that formed at Medicine Lake volcano and describe their textures.

23 Why are there ocean basins, continents, and mountains? Non-explosive volcanism. Volcanoes under the sea. Mid-Atlantic Ridge pillow basalt. How do the pillow textures in these rocks form?

24 Why are there ocean basins, continents, and mountains? How rocks deform. Deformed rocks. Deformed conglomerates. What happens to the pebbles in the rock during deformation?

25 Why are there ocean basins, continents, and mountains? How rocks deform. Deforming rocks in the laboratory. Describe how the marble cylinders responded to increasing pressure and temperature.

26 Why are there ocean basins, continents, and mountains? Earthquakes where plates collide. What is a fault? Fault in Crystalline rock. Observe the fault and the layers of rock that are displaced in rock #1. What type of fault is this? Did this rock experience compressional or extensional stress based on the fault type?

27 Choose a rock, interactive, video, or exhibit that you find interesting. Discuss in several sentences what you find interesting about this exhibit.

Appendix 1 - Igneous Rocks

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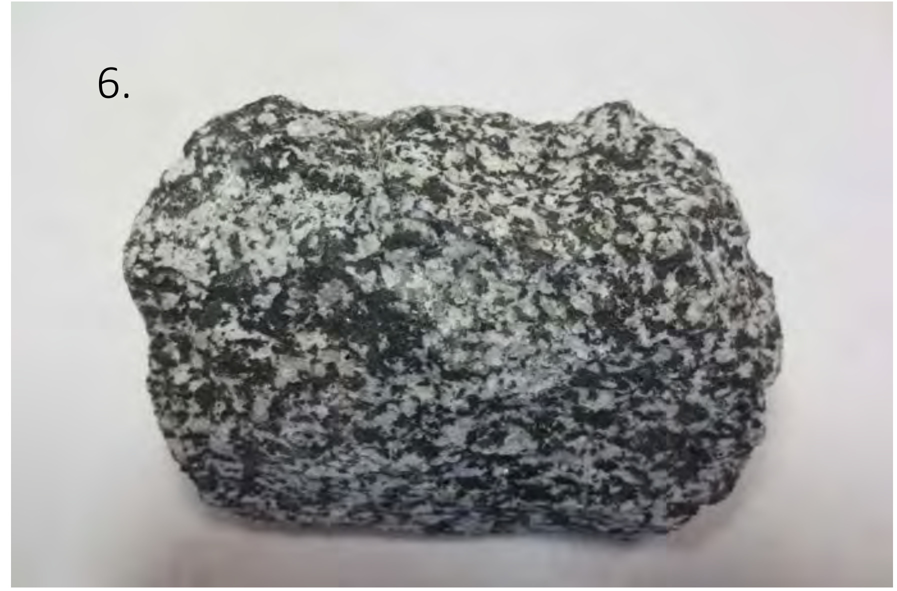

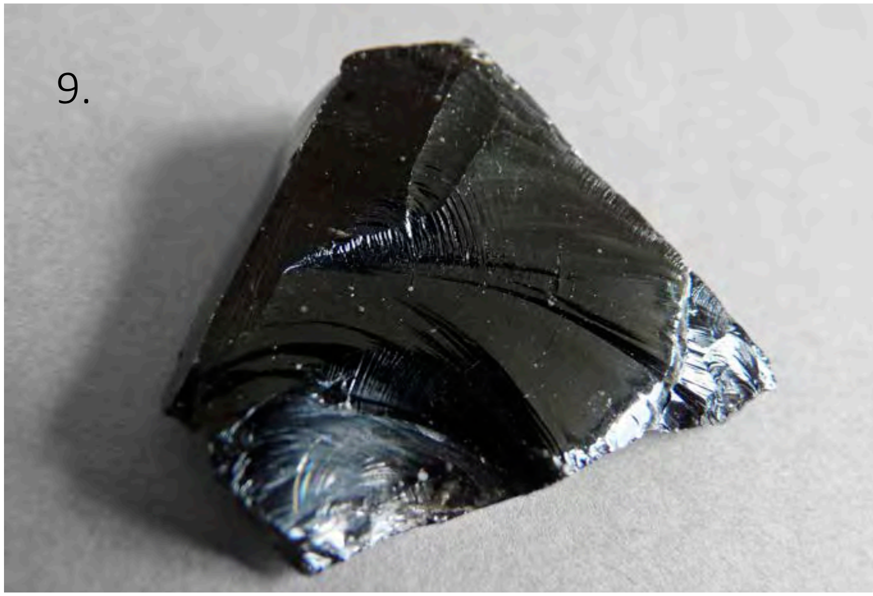
9.


10.

Appendix 2 - Sedimentary Rocks

St. John CC [partly hidden]

2.

James St. John CC BY 2.0

3.

Amcyrus2012, CC BY 4.0

4.

Amcyrus2012, CC BY 4.0


5.
Reacts with HCl acid
By Jim Stuby

6.

USGS


Reacts with HCl acid
7.
James St. John CC BY 2.0


8.
Reacts with HCl acid

9.

10.

Appendix 3 - Metamorphic Rocks

1.

2.

3.

4.

Appendix 3 - Metamorphic Rocks