LABORATORY MANUAL FOR EARTH SCIENCE

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Physical Geology Laboratory

In this class, students will explore diverse topics in the geosciences at a high level. Students who complete this class will have had the opportunity acquire the skills needed to engage in advanced geologic study.

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Lab 1—Field Notes and Observations

EFFECTIVE SCIENTIFIC COMMUNICATION

> "What is it that we human beings ultimately depend on? We depend on our words. We are suspended in language. Our task is to communicate experience and ideas to others."

—Niels Bohr

Today we will be focusing and collecting data and using that data to communicate science to others. Please read through the procedure and the recommended components for your field notes. **When class is concluded today, take these notes home to write up your lab.** You will be writing this in a standard lab report format:

1. Introduction
    a. What is the topic of this lab?
    b. What did you already know about this topic? Cite sources for this knowledge.
    c. What scientific question or problem are you addressing?
2. Method
    a. What materials did you use?
    b. How did you use them?
3. Results
    a. What data did you get during the lab?
    b. This section is for objective data reporting only.
    c. You may scan or photograph work you did in your lab manual to include as figures here.
4. Discussion
    a. What trends do you see in your data?
    b. What patterns do you observe?
    c. If you have multiple data sets, how do they compare to one another?
5. Conclusion
    a. Did you answer the scientific question you posed in the introduction? If so, what did you conclude?
    b. Or, did you address the scientific problem you described in the introduction?
    c. What did you learn?
    d. What research do you think is still needed on this topic?

Turn in this lab report—not your original lab notes—to your instructor before the beginning of next week's lab class meeting.

FIELD NOTES ACTIVITY

Objective: Through designed exercises, students will be given the opportunity to gain an appreciation of the importance of maintaining thorough, well-organized field notes on every fieldwork outing in order to support data collection for research and publication.

MATERIALS

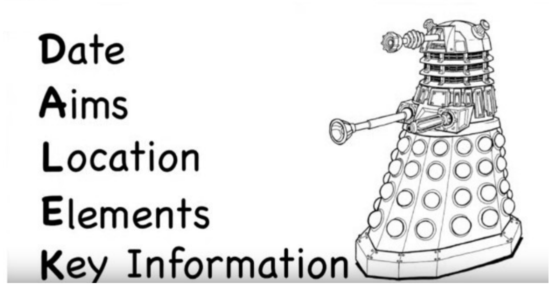
- Pencils—writing pencils and colored pencils
- Lab Manual
- Survey tape, rulers, compasses, protractors, erasers, and any other field gear that's important for you to collect your data

ACTIVITY PROCEDURE

- Walk to field site.
- Individually, in pairs, or in groups—student's choice—select a location at our class's field site and create a field notebook entry incorporating elements listed on reverse of this page.
- Study these rocks and gather as much detail as you can in your field notes. Then when you write your lab report you will be able to construct a story to share your ideas about the possible depositional environment of these rocks.
- Get with a partner to discuss your field notes.
- The whole class regroups. One student from each pair shares something they have learned with the group.

RECOMMENDED COMPONENTS OF FIELD NOTES

While your field notes should contain all the information you need to use to communicate the scientific results of your field work, sometimes it is a challenge to decide exactly what to put in that field notebook when you first start a project. Some basic components you need to have include your name, the names of other participants in this field work, page numbers, the date, the field location, the name of the project, the objectives for the day, and results pertaining to those objects. Results can include written descriptions of your observations, sketches of what you observe, measured data, and anything else you think is important. An acronym you can use to help you remember the essentials is "DALEK:" date, aims, locations, elements, key information (Grinham, 2016a).



FIELD SKETCHES

A useful acronym to help you get started with drawing field sketches is "OASIS:" orientation, annotation, scale, information, and "sketch what you see!" (Grinham, 2016b) While many people find field sketching daunting at first, drawing scientifically accurate sketches is one of the most important skills for a field geologist and is developed over time through much practice. The last S in OASIS is a key piece of advice pertaining to field sketches, and that is, "sketch what you see." Go slowly and include as much detail as you can. Sometimes, through taking your time and sketching everything, you will see more than if you were to just take a photograph. I recommend doing both. You can then reflect upon multiple representations of the same field site when you return to process your data. Here is further description of the components covered by OASIS:

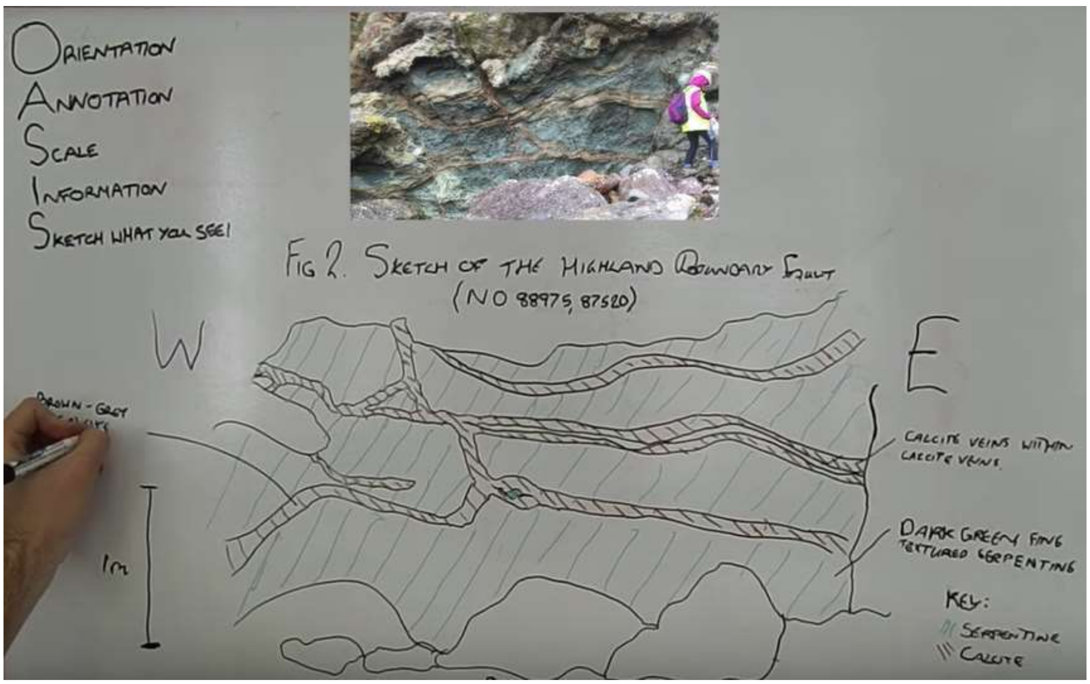


FIGURE 2. "OASIS" ACRONYM WITH AN EXAMPLE SKETCH (SCREENSHOT FROM GRINHAM, 2016B)

- Orientation—include the location and compass directions with your sketch. This may be as simple as a place name and a north arrow or as detailed as UTM coordinates or latitude and longitude with azimuth angles.
- Annotation—label everything you can
- Scale—make this as accurate as possible so you know the relative and absolute sizes of objects in your sketch
- Information—include any additional information you will need to refer too later such as the key shown in the lower right of Figure 2, and it cannot be stated enough times,
- Sketch what you see!

INSPIRATION HUT - 0.8CM RULED

graph paper – Andrew Davidhazy – andpph@rit.edu

graph paper – Andrew Davidhazy – andpph@rit.edu

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NOTES

Lab 2—Mineral identification

The geological definition of a mineral is, “a naturally occurring crystalline solid substance, generally inorganic, with a specific chemical composition.” (Press and Siever, 2004)

PHYSICAL PROPERTIES OF MINERALS

The most commonly used physical properties used to identify minerals are 1. color, 2. luster, 3. hardness, 4. streak, 5. cleavage or fracture, and 6. crystal habit. In this lab, you will describe and classify mineral samples using each of these properties.

1. **Color**

Color is often the first property used when initially trying to identify a mineral. However, color can be misleading when determining a specific mineral and it should not be relied upon too heavily. Also, remember to note the clarity of the color in the mineral. Descriptive terms for clarity include transparent, translucent, and opaque.

2. **Luster**

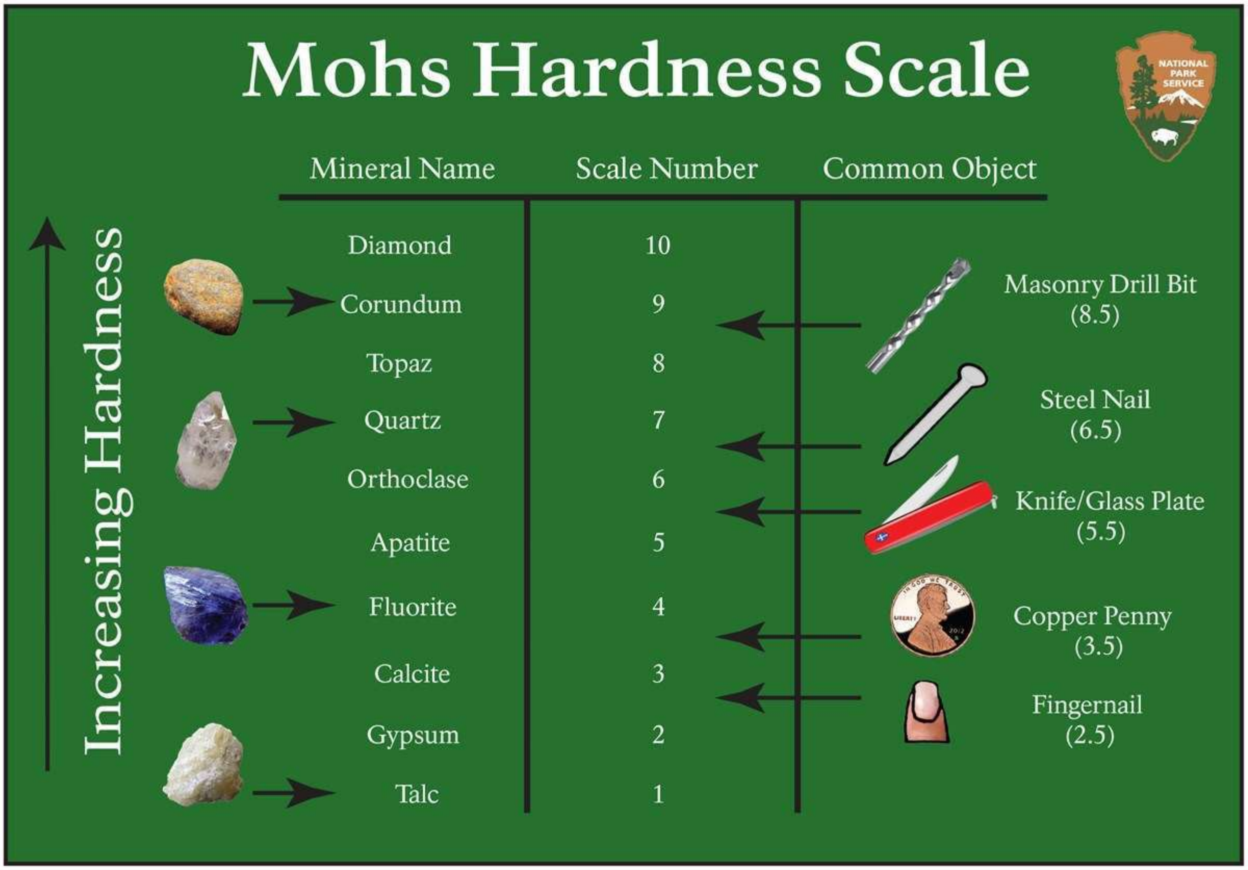
Luster describes the way light interacts with the surface of a mineral or rock. Due to light reflecting off a mineral, it can appear metallic or non-metallic. Non-metallic lusters are further subdivided into several categories as listed below.

- Metallic
- Non-metallic
    - Vitreous (glassy)
    - Dull (earthy)
    - Resinous
    - Waxy
    - Greasy
    - Pearly

3. **Hardness**

Mohs Hardness (H) is a measure of the resistance of a mineral to scratching (not breaking, as in along cleavage planes), or the resistance a smooth surface offers to abrasion.

TABLE 2.1 MOHS SCALE OF HARDNESS (NPS, 2019)



4. **Streak**

Refers to the color of a powdered mineral. This is more consistent than the color of a whole crystal and therefore provides a more reliable feature for mineral identification. You can obtain this by scratching the mineral on an unpolished piece of white porcelain called a streak plate.

5. **Cleavage or fracture**

Cleavage is the tendency of a mineral to break along smooth parallel flat surfaces. These reveal the underlying atomic structure of the mineral. Remember to include these aspects of the mineral's cleavage:

- How many cleavage planes are apparent?
- How strong/apparent is cleavage? (excellent, good, poor, no cleavage)
- At what angle do cleavage plains meet? (90° or 60° & 120° are most common, other angles are possible)

Fracture is the result of a mineral having no cleavage planes, and represents a mineral's tendency to display random, irregular breakage, or breakage along non-parallel planes. Commonly observed fracture patterns include *conchoidal* and *splintery* fracture. Conchoidal minerals break along surfaces that then display concentric circle patterns, while rocks with splintery fracture break along multiple surface with the resulting pattern resembling splintered wood.

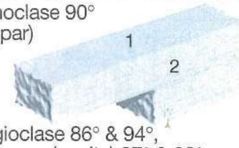
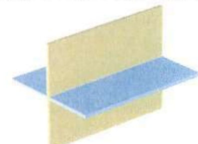
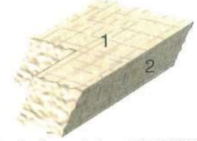
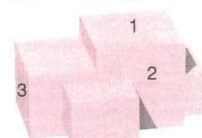
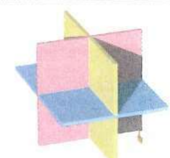
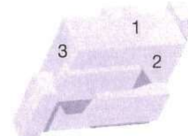
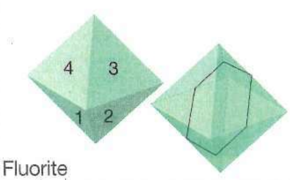
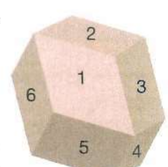
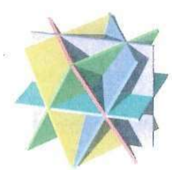
Number of Cleavages and Their Directions	Name and Description of How the Mineral Breaks	Shape of Broken Pieces (Cleavage Directions are Numbered)	Illustration of Cleavage Directions
No cleavage (fractures only)	No parallel broken surfaces; May have conchoidal fracture (like glass)	Quartz	None (no cleavage)
1 cleavage	**Basal (book) cleavage** "Books" that split apart along flat sheets	 Muscovite, biotite, chlorite (micas)	
2 cleavages intersect at or near 90°	**Prismatic cleavage** Elongated forms that fracture along short *rectangular* cross sections	Orthoclase 90° (K-spar)  Plagioclase 86° & 94°, pyroxene (augite) 87° & 93°	
2 cleavages do not intersect at 90°	**Prismatic cleavage** Elongated forms that fracture along short *parallelogram* cross sections	 Amphibole (hornblende) 56° & 124°	
3 cleavages intersect at 90°	**Cubic cleavage** Shapes made of cubes and parts of cubes	 Halite, galena	
3 cleavages do not intersect at 90°	**Rhombohedral cleavage** Shapes made of rhombohedrons and parts of rhombohedrons	 Calcite and dolomite 75° & 105°	
4 main cleavages intersect at 71° and 109° to form octahedrons, which split along hexagon-shaped surfaces; may have secondary cleavages at 60° and 120°	**Octahedral cleavage** Shapes made of octahedrons and parts of octahedrons	 Fluorite	
6 cleavages intersect at 60° and 120°	**Dodecahedral cleavage** Shapes made of dodecahedrons and parts of dodecahedrons	 Sphalerite	

FIGURE 2.1 CLEAVAGE IN MINERALS

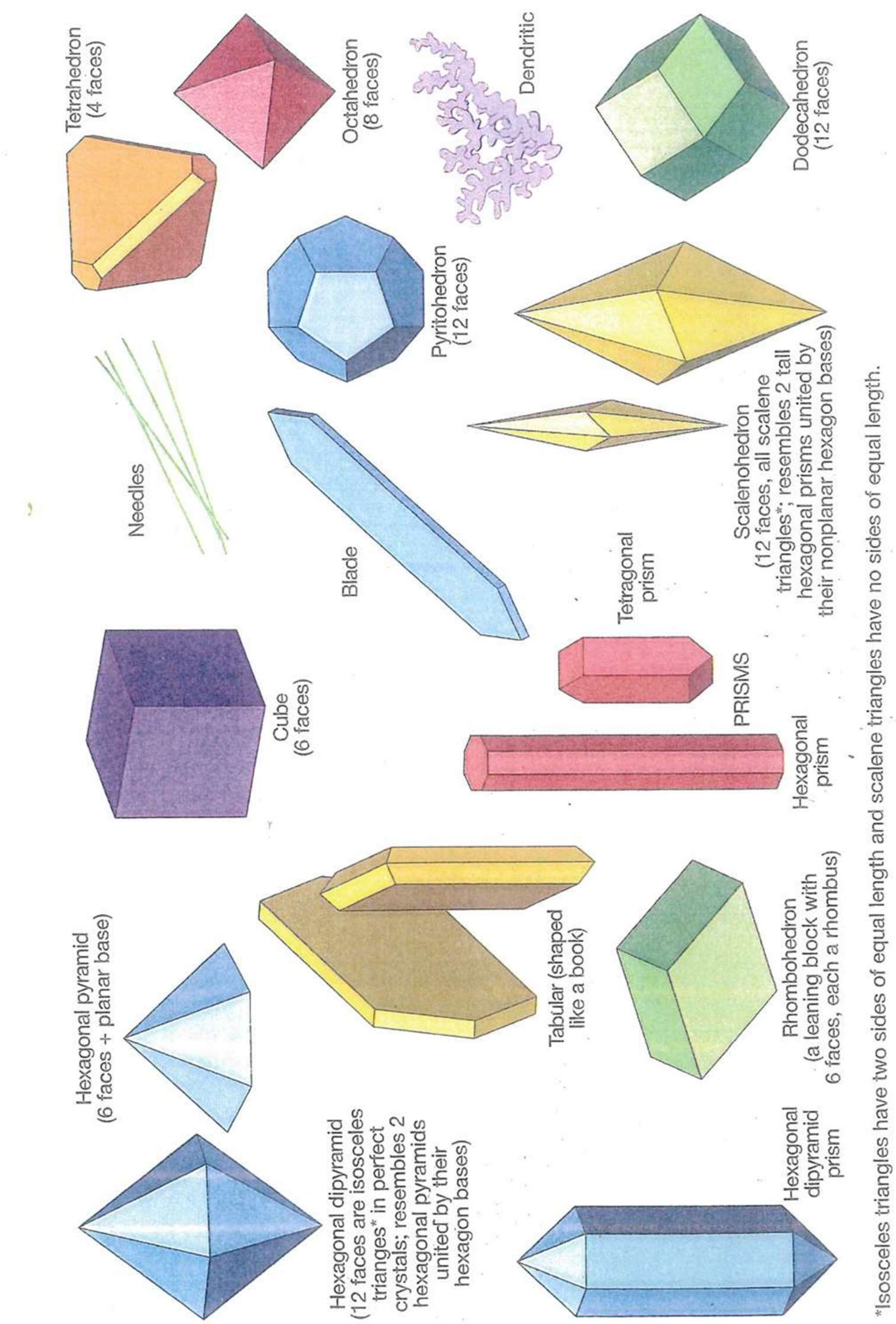


FIGURE 2.2 MINERAL HABITS

6. **Crystal habit**

Crystal habits are the distinctive form or shape that a mineral may take in different geologic settings. Habits describe the ideal growth form of the mineral (with well-formed crystal faces), provided the mineral has the free space to complete unhindered growth. Here are some examples of crystal habit or form: cubic, octahedral, tabular (rectangular), acicular (long, slender, needle- like), fibrous, dendritic (branching like a tree), or botryoidal (smooth, bulbous).

Other Useful Properties

- Magnetism
- Taste / Odor / Feel
- Tenacity—how a mineral resists breakage. Is the mineral Elastic? Flexible? Brittle?
  Malleable?
- Reaction to Acid—Carbonate minerals, such as calcite, tend to react with hydrochloric acid (HCl). This reaction is referred to as effervescence. It is important to note whether the mineral effervesces strongly with acid or weakly.
- Specific Gravity—How heavy does the mineral feel? Is it particularly heavy or dense?
  Light?
- Striations—fine, straight "scratches" visible on the surface of specific minerals, such as plagioclase feldspar

MINERAL IDENTIFICATION FLOW CHART

To identify each mineral sample, start by observing the mineral's luster: metallic, non-metallic with a lighter color, or non-metallic with a darker color. In the mineral descriptions, listed within parentheses are the rock types in which that mineral is commonly found: I = igneous, M = metamorphic, S = sedimentary.

1. Is the mineral's luster metallic?
   a. If NO, go to **2**.
   b. If YES, continue with **Metallic Luster Chart**:

Streak Color	*Mineral Color*	*Other properties*	*Mineral Name*	*Chemical Formula*
black, gray or greenish black	bright metallic silver-gray	very heavy (ρ=7.6), cubic crystal habit, H=2.5 (M)	Galena	PbS
	black to dark gray	strongly magnetic, ρ=5.2, H=6 (**I**, S)	Magnetite	Fe_3O_4
	steel gray	smudges fingers, shiny, slippery, ρ=2, H=1 (**I**, M)	Graphite	C
	brass yellow	cubic crystal habit, striations common, common in granular aggregates, uneven fracture, ρ=6–6.5, H=5	Pyrite	FeS_2
greenish black	golden yellow	may tarnish purple, may be weakly magnetic, streak is greenish black, ρ=4, H=4.3	Chalcopyrite	$CuFeS_2$
brown to reddish brown	red-brown, steel gray, or black	granular, fibrous, or micaceous, uneven fracture (S)	Hematite	Fe_2O_3
yellow or brown	yellow, brown, or black	hard, structureless, or radial fibrous masses; can be cubic as pseudomorph after pyrite, ρ=5, H=5–6 (S)	Limonite	$FeO(OH)\cdot nH2O$
metallic copper red	copper red, tarnishes to dull brown	often found as distorted masses or extremely distorted crystals, ρ=8.9, H=2.5–3 (I, M, S)	Native Copper	Cu

2. **Non-metallic luster**: Is the mineral's color lighter or darker?
   a. If non-metallic luster with lighter color, go to **3**.
   b. If non-metallic luster with darker color, go to **4**.

3. **Non-metallic luster with lighter color**: Does the mineral scratch glass?
   a. If YES, use this chart:
   Non-metallic luster, lighter color, harder than glass:

Demonstrates cleavage?	*Other properties*	*Mineral Name*	*Chemical Formula*
cleavage prominent	2 cleavage planes at almost 90°, light to dark pink, blocky, pearly to vitreous luster, ρ=2.5, H=6–6.5 (**I**, M, S)	Orthoclase feldspar	$KAlSi_3O_8$
	2 cleavage planes at almost 90°, white to gray to bluish gray, blocky, striations on some cleavage planes, ρ=2.6–2.8, H=6–6.5 (**I**, M, S)	Plagioclase feldspar	$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$

cleavage absent	conchoidal fracture, glassy, transparent to translucent, hexagonal crystal habit, well-formed crystals common, varieties named by color: milky, smoky, rose, and amethyst, ρ=2.65, H=7 (I, M, S)	Quartz	SiO_2
	conchoidal fracture, translucent to opaque, dull or clouded luster, white, yellow, gray, black, or brown, sometimes banded, dull and opaque, ρ=2.7, H=6.5–7 (I, M, S)	Cryptocrystalline quartz	SiO_2

b. If NO, use this chart:
Non-metallic luster, lighter color, softer than glass:

Demonstrates cleavage?	*Other properties*	*Mineral Name*	*Chemical Formula*
cleavage prominent	perfect cubic cleavage, salty taste, colorless, white or pale orange, forms cubes, soluble in water, ρ=2, H=2–2.5 (S)	Halite	$NaCl$
	white to gray to bluish gray, blocky, striations on some cleavage planes, ρ=2.6–2.8, H=6–6.5 (I, M, S)	Gypsum	$CaSO_4 \bullet 2H_2O$
	perfect rhombohedral cleavage, at about 75° (squashed cube), effervesces in HCl, white or colorless, transparent to opaque, ρ=2, H=2–2.5 (S, M)	Calcite	$CaCO_3$
	4 good cleavage directions; colorless, green, purple, yellow or brown, glassy; transparent to translucent; cubic crystal habit, ρ=3, H=4 (I, M, S)	Fluorite	CaF_2
	one perfect cleavage plane, thin flexible sheets, colorless to light yellow, ρ=2.8, H=2–3 (M, S)	Muscovite	$KAl_3AlSi_3O_{10}(OH)$
	gray, pink or white, greasy or soapy feel, pearly luster, one direction of cleavage forms thin scales, foliated or compact masses, ρ=2.8, H=1 (M)	Talc	$Mg_3Si_4O_{10}(OH)_2$
cleavage absent	crystals so small no cleavage is visible, white to red, earthy masses, soft, becomes plastic when moistened, earthy odor, H=1.2 (I, M, S)	Kaolinite	$Al_4Si_4O_{10}(OH)_8$
	crystal habit: well-shaped hexagonal crystals, which may be prismatic, dipyramidal, and stubby; colorless, white, yellow, brown, gray, red, pink, purple, blue, green; transparent to translucent; ρ=3.1–3.2, H=5 (I, M)	Apatite	$Ca_5(PO_4)_3F$
	bright yellow to yellow-brown, greasy feel, exhibits a strong "rotten-egg" odor, soluble in warm water, ρ=2.0–2.1, H=1.5–2 (I, S)	Sulfur	S

4. **Non-metallic luster with darker color**: Does the mineral scratch glass?

   a. If YES, use this chart:

   Non-metallic luster, darker color, harder than glass:

Demonstrates cleavage?	*Other properties*	*Mineral Name*	*Chemical Formula*
cleavage prominent	2 cleavage planes at almost 90°, black to dark green, short, prismatic, 8-sided crystals, ρ=3.5, H=6 (**I**)	Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$
	2 cleavage planes ~60° and 120°, dark green to black or brown, long prismatic 6-sided crystals, ρ=2.9–3.5, H=6 (**I**, M)	Hornblende	$(Ca,Na)_{2–3}(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH,F)_2$
	2 cleavage planes at almost 90°, gray to dark blue-gray, blocky, striations on some cleavage planes, ρ=2.6–2.8, H=6–6.5 (**I**, M, S)	Plagioclase feldspar	$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$
cleavage absent	bright to dark green, glassy luster, usually in granular masses, transparent to translucent, ρ=3.5–4.5, H=6.5–7 (**I**)	Olivine	$(Mg,Fe)_2SiO_4$
	red color most common, other colors possible, glassy to resinous luster, conchoidal to uneven fracture, ρ=3.1–4.3, H= 6.5–7.5 (**I**, M)	Garnet	$(Ca,Mg,Fe,Mn)_3(Al,Fe,Cr)_2(SiO_4)_3$
	conchoidal fracture, gray to gray-black, vitreous luster, transparent to translucent, hexagonal crystal habit, well-formed crystals common, ρ=2.65, H=7 (**I**, M, S)	Smoky quartz	SiO_2

   b. If NO, use this chart:

   Non-metallic luster, darker color, softer than glass:

Demonstrates cleavage?	*Other properties*	*Mineral Name*	*Chemical Formula*
cleavage prominent	one perfect cleavage plane, flexible and elastic when in thin sheets, brown to black, ρ=3–3.5, H=2.5–3 (M, S)	Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$
	green to very dark green, 1 cleavage direction, foliated or scaly masses, ρ=2.5–3.5, H=2–2.5 (M)	Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2(Mg,Fe)_3(OH)_6$
	yellowish brown, resinous luster, cleavage in 6 directions, yellowish brown or nearly white streak, ρ=4, H=3.5–4 (**I**, M, S)	Sphalerite	$(Zn,Fe)S$
	4 good cleavage directions; colorless, green, purple, yellow or brown, glassy; transparent to translucent; cubic crystal habit, ρ=3, H=4 (**I**, M, S)	Fluorite	CaF_2
cleavage absent	red to red-brown streak, earthy appearance H=1.5 (S)	Hematite	Fe_2O_3
	Yellowish-brown streak, yellowish brown to dark brown; hard, structureless, or radial fibrous masses; can be cubic as pseudomorph after pyrite, ρ=5, H=5–6 (S)	Limonite	$FeO(OH)\cdot nH2O$
	bright yellow to yellow-brown, greasy feel, exhibits a strong "rotten-egg" odor, soluble in warm water, ρ=2.0–2.1, H=1.5–2 (**I**, S)	Sulfur	S

Mineral Identification Table for Lab 2

Sample Number	Luster	Hardness (H)	Cleavage or Fracture	Color	Streak	Crystal Habit and/or other properties	Mineral Name
1							
2							
3							
4							
5							
6							
7							
8							
9							

Sample Number	Luster	Hardness (H)	Cleavage or Fracture	Color	Streak	Crystal Habit and/or other properties	Mineral Name
10							
11							
12							
13							
14							
15							
16							
17							
18							

Sample Number	Luster	Hardness (H)	Cleavage or Fracture	Color	Streak	Crystal Habit and/or other properties	Mineral Name
19							
20							
21							
22							
23							
24							
25							
26							

NOTES

Lab 3—Rock cycle and plate tectonics

Minerals are the building blocks that make up rocks. Rocks are grouped into three categories, determined by the way the rocks were formed: igneous, metamorphic, and sedimentary. Rocks are then identified by the minerals they are made up and the way in which they were formed.

THE ROCK CYCLE

The formation of these three categories of rocks can be thought of as occurring in a cycle. In this cycle, magma comes up from the mantle of the earth. It either cools inside the crust to form intrusive igneous rocks or exits by volcanoes to cool on the surface, resulting in extrusive igneous rocks. Igneous rocks and sedimentary rocks can be buried deep within the crust, and then through exposure to high temperatures and pressures, they change physically and chemically into metamorphic rocks. Rocks from all three categories can be broken down by weathering processes, transported, redeposited, and then formed into sedimentary rocks.

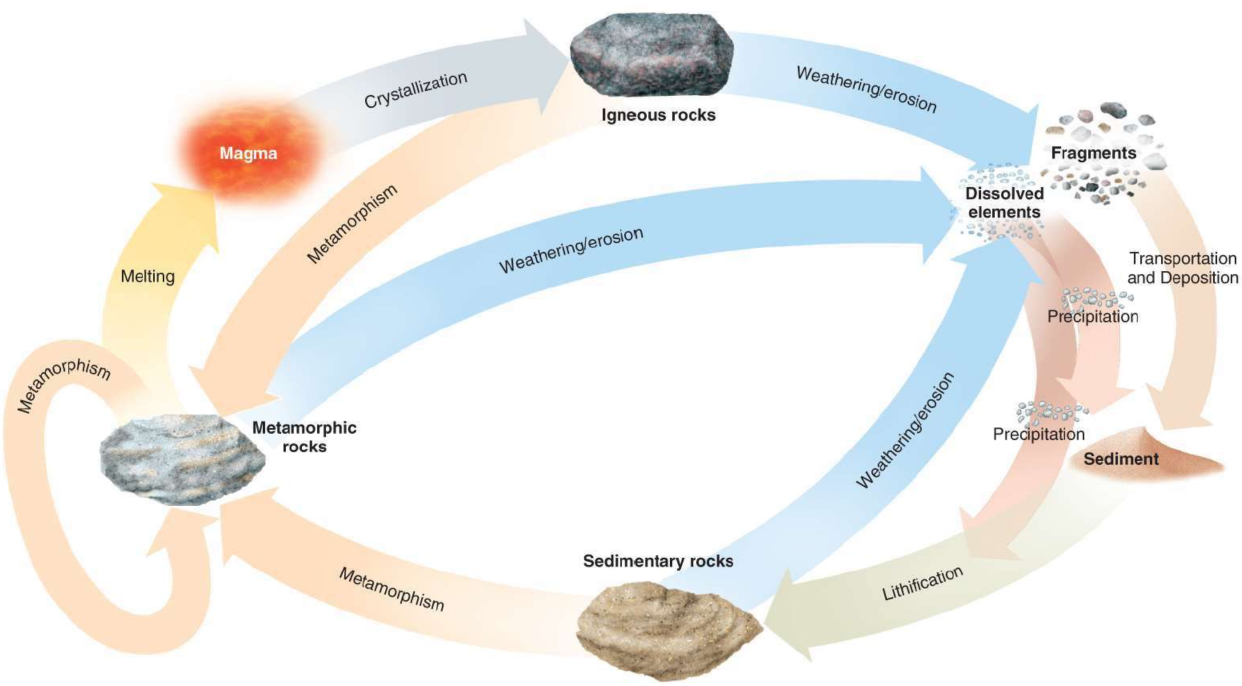


FIGURE 3.1 THE ROCK CYCLE

STRUCTURE OF THE EARTH

Our earth can be thought of as spherical, consisting of three major concentric layers from outside to the center: the crust, the mantle, and the core. These layers are further subdivided according to their composition and physical behaviors. The earth's crust, both the oceanic and continental crust are made up of the rocks described above in the rock cycle. The boundary between the crust and the mantle, also known as the Moho, is defined by a change in the way that earthquake waves propagate through those materials. The uppermost mantle is solid; it moves in tectonic plates with the crust, and the two together are called the lithosphere. The lithospheric plates ride on the viscous asthenosphere, or lower mantle. The convection currents in the asthenosphere drive the process of plate tectonics. Below the mantle is earth's core, consisting predominantly of iron and nickel: a solid inner core surrounded by a liquid outer core. It is believed that the convection of the liquid metal outer core induces the earth's magnetic field.

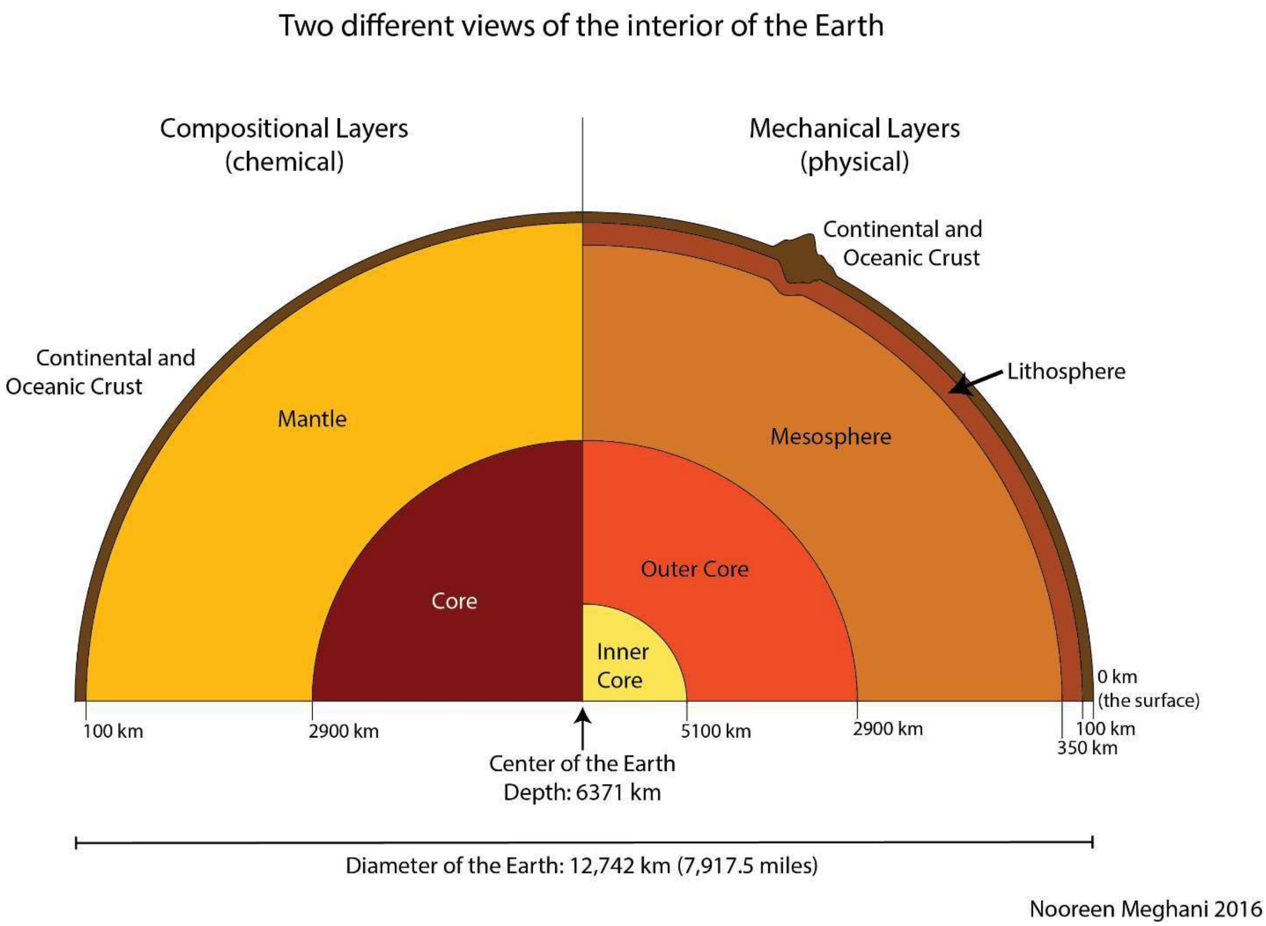


FIGURE 3.2 EARTH'S LAYERS (MEGHANI, 2016)

PLATE TECTONICS

Alfred Wegener is widely recognized as the first person to put forth, in 1929, the concept of continental drift that would serve as the basis for the theory of plate tectonics. He wrote: "The forces which displace continents are the same as those which produce great fold-mountain ranges. Continental drift, faults and compressions, earthquakes, volcanicity, transgression cycles, and polar wondering are undoubtedly connected causally on a grand scale. Their common intensification in certain periods of the earth's history shows this to be true. However, what is cause and what effect, only the future will unveil."

With advances in technology and increased understanding about the way that earth's magnetic orientation changes periodically, bands of oceanic crust were discovered with alternating magnetic alignments, creating stripes as it were, symmetrically about the mid-ocean ridges. The creation of new oceanic crust at these oceanic crust centers must be balanced by destruction of old crust. Thus, the driving force of mantle convection was deduced.

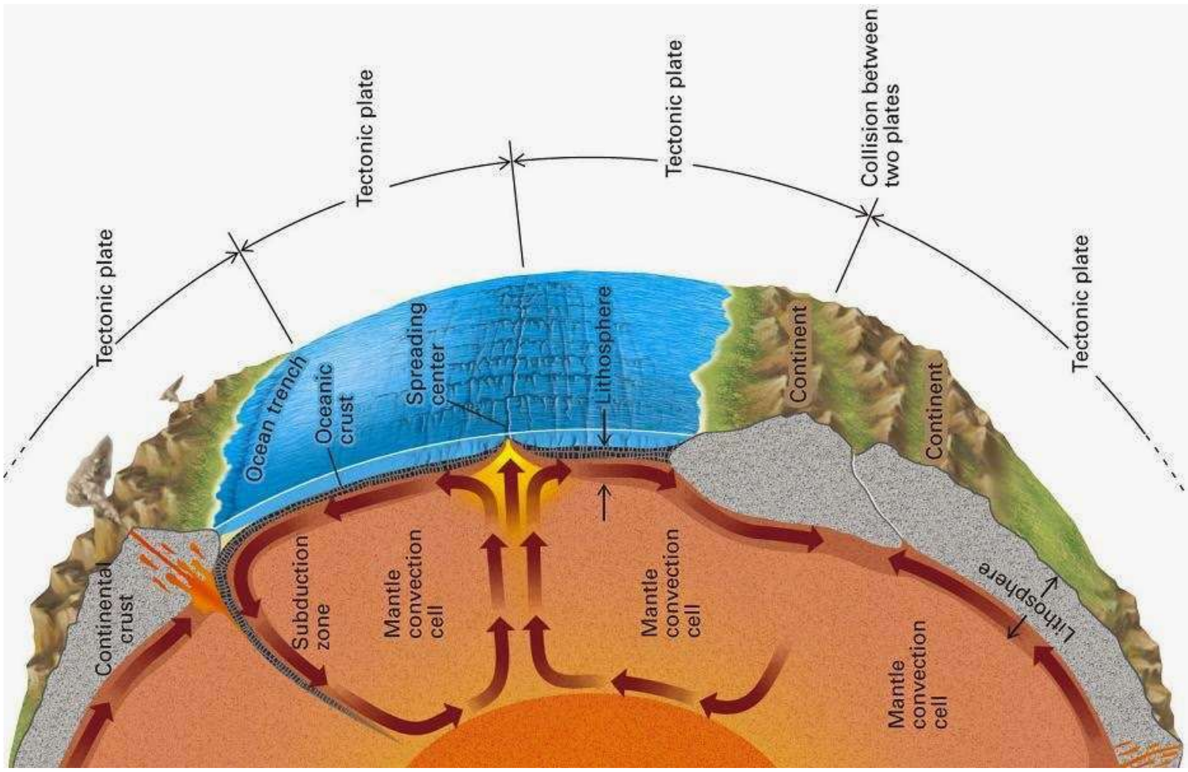


FIGURE 3.3 MANTLE CONVECTION AND ITS RELATION TO PLATE TECTONICS

Together, this mantle convection and the observation that the earth's continents appear to fit like puzzle pieces fomented a scientific revolution. Plate tectonics emerged as a dominant geologic theory in the mid-twentieth century.

"The Himalayas are the crowning achievement of the Indo-Australian plate. India in the Oligocene crashed head on into Tibet, hit so hard that it not only folded and buckled the plate boundaries but also plowed into the newly created Tibetan plateau and drove the Himalayas five and a half miles into the sky. The mountains are in some trouble. India has not stopped pushing them, and they are still going up. Their height and volume are already so great they are beginning to melt in their own self-generated radioactive heat. When the climbers in 1953 planted their flags on the highest mountain, they set them in snow over the skeletons of creatures that had lived in a warm clear ocean that India, moving north, blanked out. Possibly as much as 20,000 feet below the sea floor, the skeletal remains had turned into rock. This one fact is a treatise in itself on the movements of the surface of the earth. If by some fiat, I had to restrict all this writing to one sentence; this is the one I would choose: the summit of Mount Everest is marine limestone."

— **John McPhee, Annals of the Former World**

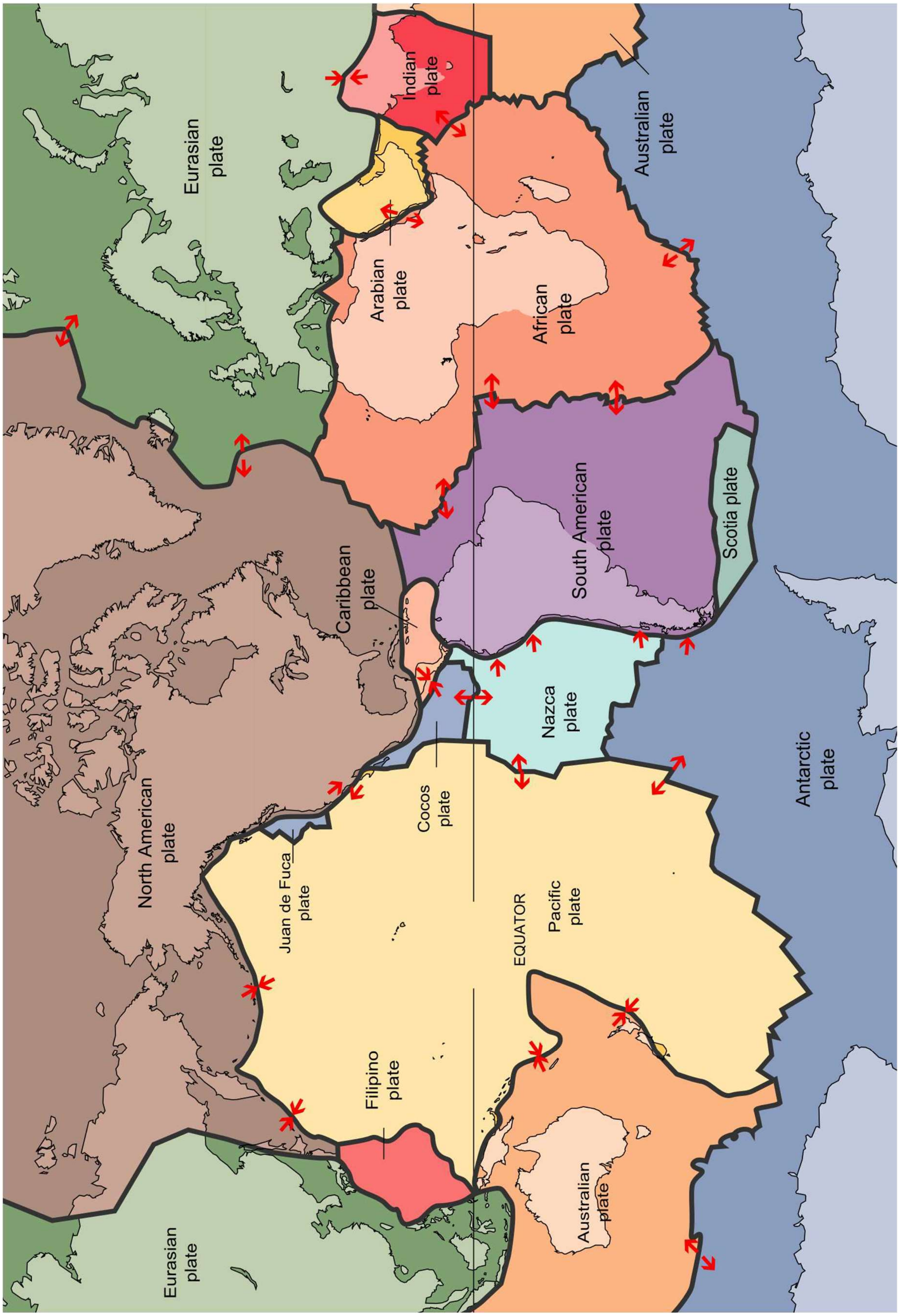


FIGURE 3.4 TECTONIC PLATES (NASH, 1996)

Lab Questions for The Rock Cycle and Plate Tectonics
A Closer Look at the Rock Cycle

1) Examine the igneous, sedimentary and metamorphic rock samples provided. Discuss with your classmates some of the similarities and differences between the three rock types. Then, discuss some of the processes that lead to the formation of each rock type.

   1a) List at least one characteristic that makes each rock type distinctive. Conversely, what is similar about all three rock types?

   1b) List at least 1 process each that could lead to the formation of an igneous rock, a sedimentary rock, and a metamorphic rock.

Density of Earth's Crust
The Earth's crust can be divided into two categories: Oceanic and Continental.

- **Continental crust** is composed primarily of **granite**
- **Oceanic crust** is composed primarily of **basalt**

Though both granite and basalt are considered igneous rocks, they have different elemental compositions. Basalt is *slightly* more enriched in iron, magnesium, and nickel than granite, which has oxygen, aluminum, and silicon. (Take a look at the periodic table in the back of this manual to determine which of these elements are denser than others.)

2) Look at the samples of granite and basalt provided. Note your observations about each type of rock.

   Granite

   Basalt

3) Scientific hypothesis: Which of these two rocks do you think is denser?

4) Test with Experimentation: Calculate the density of 2 basalt and 2 granite samples using the equation, $\rho = {}^{m}/_{V}$ and filling in the chart below. Mass is provided for each sample, but you will have to calculate volume using a water displacement method. Recall that for water, 1 mL = 1 cm^3.

Sample name/Rock type	**Mass** (m, g)	**Volume** (V, mL)	**Density** ($\rho = {}^{m}/_{V}, {}^{g}/_{cm^3}$)

5) <u>Analyze the results and draw a conclusion</u> based on your experiment above. Was your hypothesis correct?

6) <u>Communicate</u> with your classmates to compare results. Are your calculated density measurements the same? If not, list 2 possible sources of error.

<u>Plate Movement</u>

To answer these questions, view this [paleogeographic animation](https://drive.google.com/file/d/1DO1hNFPxbCs8r3IZ-ajuoljmH4ivSx_5/view) (https://drive.google.com/file/d/1DO1hNFPxbCs8r3IZ-ajuoljmH4ivSx_5/view), that shows the paleogeography of the North Atlantic during the last 290 million years.

8) Can plate movement over time be best described as simple horizontal or vertical movements, as rotations, or both?

9) What type of plate margin was eastern North America during the early stages of plate movement?

10) In relation to North America, where was Africa located 250 million years ago?

11) Describe the continent of Africa’s subsequent movements.

Age of the Oceanic Crust (refer to Figure 3.5)

12) What color represents the youngest oceanic crust? What color represents the oldest oceanic crust?

13) What kind of boundary is associated with the youngest oceanic crust? How is crust formed at this type of boundary?

14) Looking at the small Philippine plate (be sure you're looking at the thin arrow, not the thick arrow):

7a) What type of boundary makes up the eastern border of the plate?
7b) What is the approximate age of the crust on the Pacific plate where it meets the Philippine plate?
7c) Is the Philippine plate subducting under the Pacific plate, or vice versa? 7d) Why does the one plate more readily subduct beneath another?

Volcanoes Around the World (refer to the Figure 3.6)

15) Do you see any relationship between the locations of volcanic chains and plate boundaries? Is this relationship specific to one type of plate boundary? Explain.

16) Does this relationship account for all volcanoes and volcanic island chains or do some follow a different trend? List two locations on the map where volcanoes/volcanic chains do not follow the trend. What, then, accounts for the locations of these volcanoes/chains?

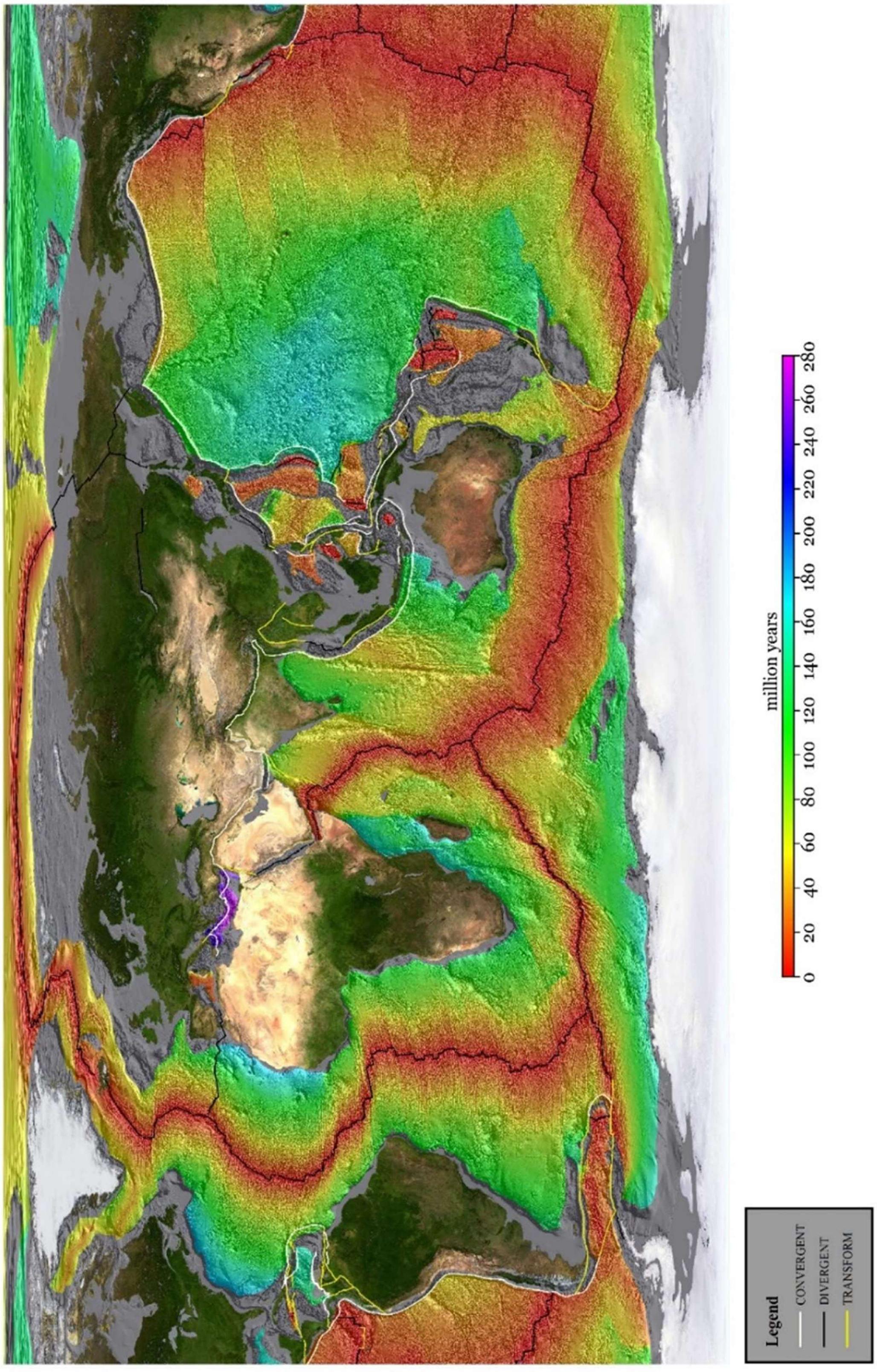


FIGURE 3.5 THE AGE OF EARTH'S OCEANIC CRUST (LIM, 2019)

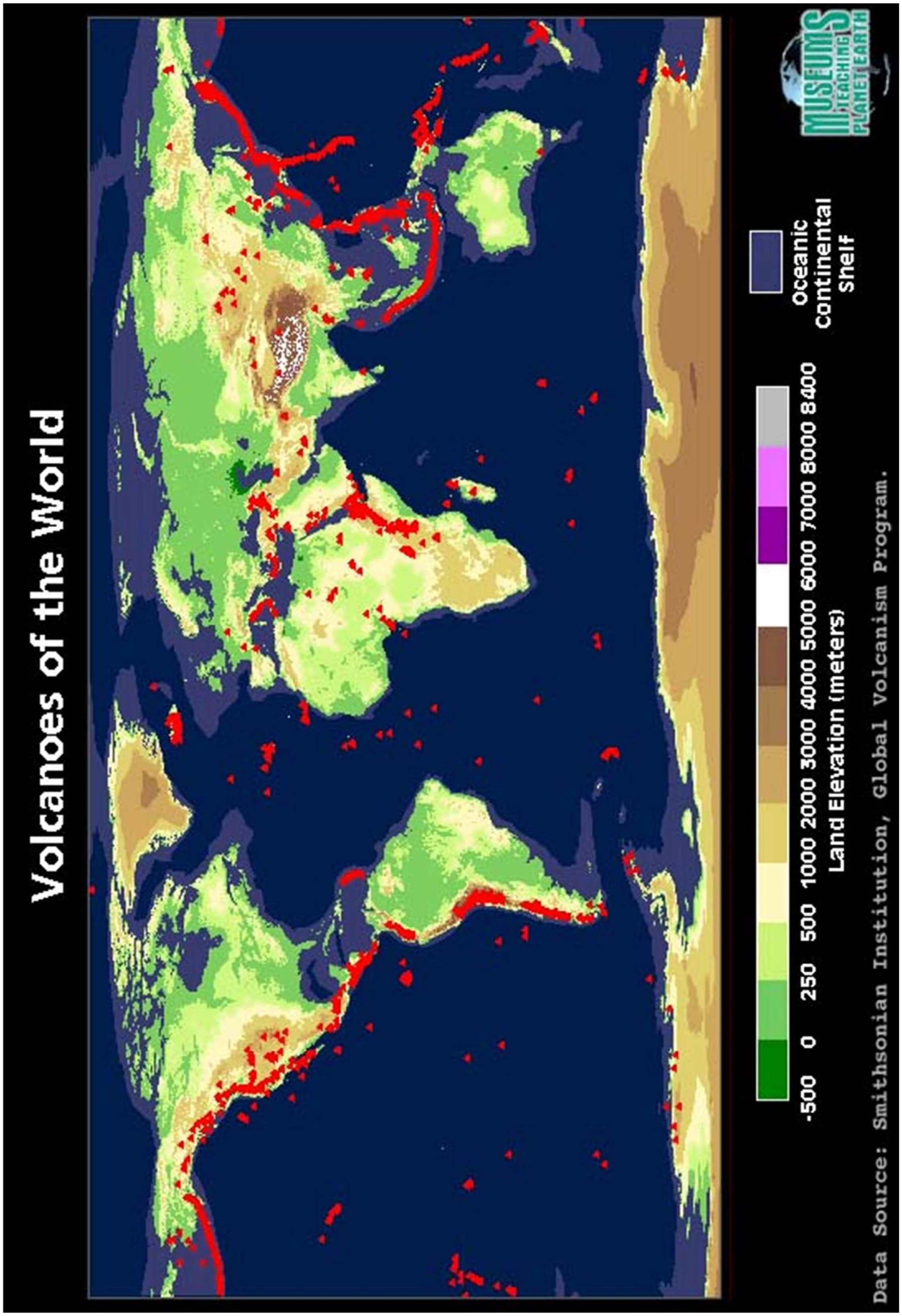


FIGURE 3.6 VOLCANOES OF THE WORLD (2019)

Earthquakes Around the World (refer to Figure 3.7)

17) Which colored circles represent the deepest earthquakes?

18) Do you see any patterns or trends in the location of earthquakes around the world?

19) What kind of plate boundaries are associated with shallower earthquakes? Deeper earthquakes?

20) The plate boundary between the Nazca Plate and the South American Plate is located just off the west coast of South America. Are the deepest earthquakes associated with this boundary located closer to the coast (and to the plate boundary), or further inland? How does this relate to the subduction of the Nazca Plate?

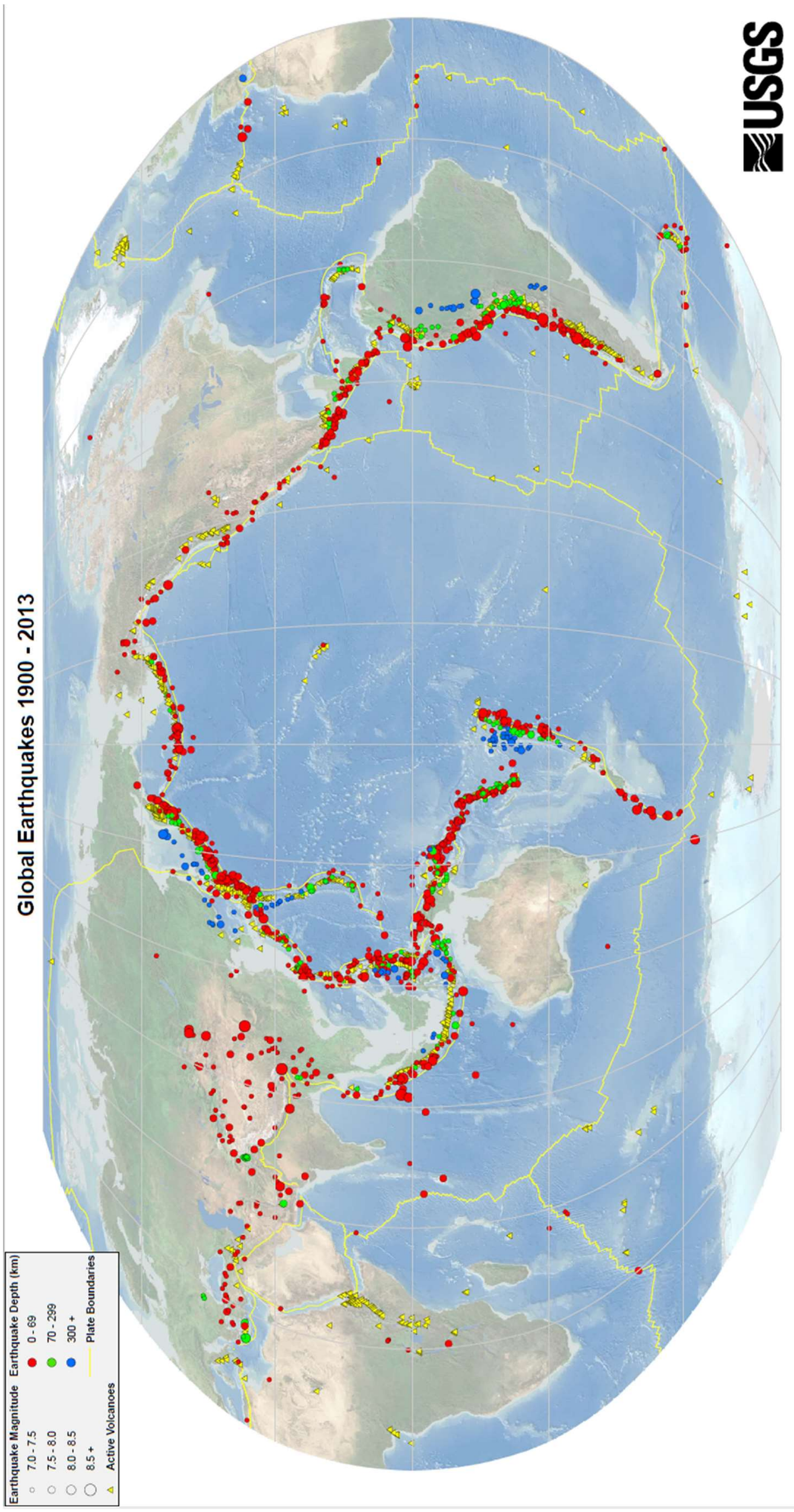

Global Earthquakes 1900 - 2013
Earthquake Magnitude
7.0 - 7.5
7.5 - 8.0
8.0 - 8.5
8.5 +
Active Volcanoes
Earthquake Depth (km)
0 - 69
70 - 299
300 +
Plate Boundaries
USGS

FIGURE 3.7 GLOBAL EARTHQUAKES (2019)

Hawaii: An Oceanic Hotspot (refer to Figure 3.8)

(Questions from Busch and Tasa: Laboratory Manual in Physical Geology, Eighth Edition, 2009) The associated figure shows the distribution of the Hawaiian Island Chain and Emperor Seamount Chain. The numbers indicate the age of each island in millions of years (m.y.), obtained from the basaltic igneous rock of which each island is composed.

21) What is the rate in cm/yr. and direction of plate motion from 4.7-1.6 million years ago?

22) What is the rate in cm/yr. and direction of plate motion from 1.6 million years ago to present time?

23) How does the rate and direction of Pacific Plate movement during the past 1.6 million years differ from the older rate and direction (4.7-1.6 m.y.) of plate motion?

24) Locate the Hawaiian Island Chain and the Emperor Seamount Chain in the upper part of the image. How are the two island chains related?

25) Based on the distribution of the Hawaiian Islands and Emperor Seamount chains, suggest how the direction of the Pacific plate movement has generally changed over the past 60 million years.

For the following questions, reading the information at this site (https://volcanoes.usgs.gov/observatories/hvo/about_earthquakes.html).

26) Are earthquakes common on the island of Hawaii? Are low magnitude or high magnitude quakes most common?

27) What are the types of Hawaiian earthquakes? Provide a brief summary of each.

28) Do you think earthquakes are as common on other islands in the Hawaiian island chain? Explain.

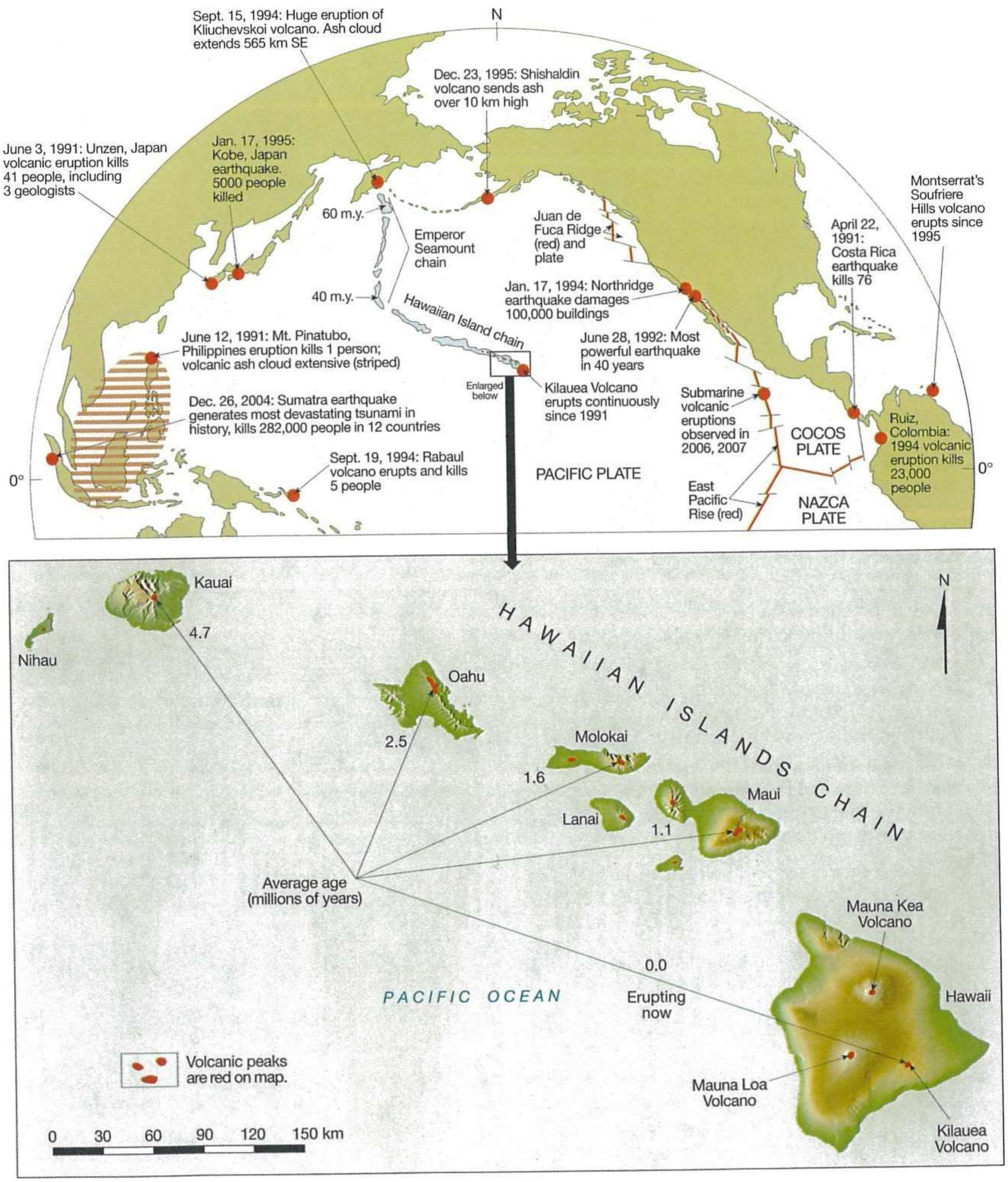


FIGURE 3.8 HAWAIIAN ISLANDS CHAIN

Yellowstone: A Continental Hotspot (refer to Figure 3.9)
(Questions from Busch and Tasa: Laboratory Manual in Physical Geology, Eighth Edition, 2009) Another good example of a hotspot is Yellowstone National Park. Although there are no volcanoes currently erupting in Yellowstone today, there are hot springs and geysers. Geologist Mark Anders has been able to reconstruct a map of circular regions that were once centered over the hotspot at specific times.

29) Based on the ages and location of each Yellowstone Hot Spot Deformation Zone, what direction is the North American Plate moving?

30) What is the average rate in cm/yr. that the North American Plate has moved over the past 11 million years?

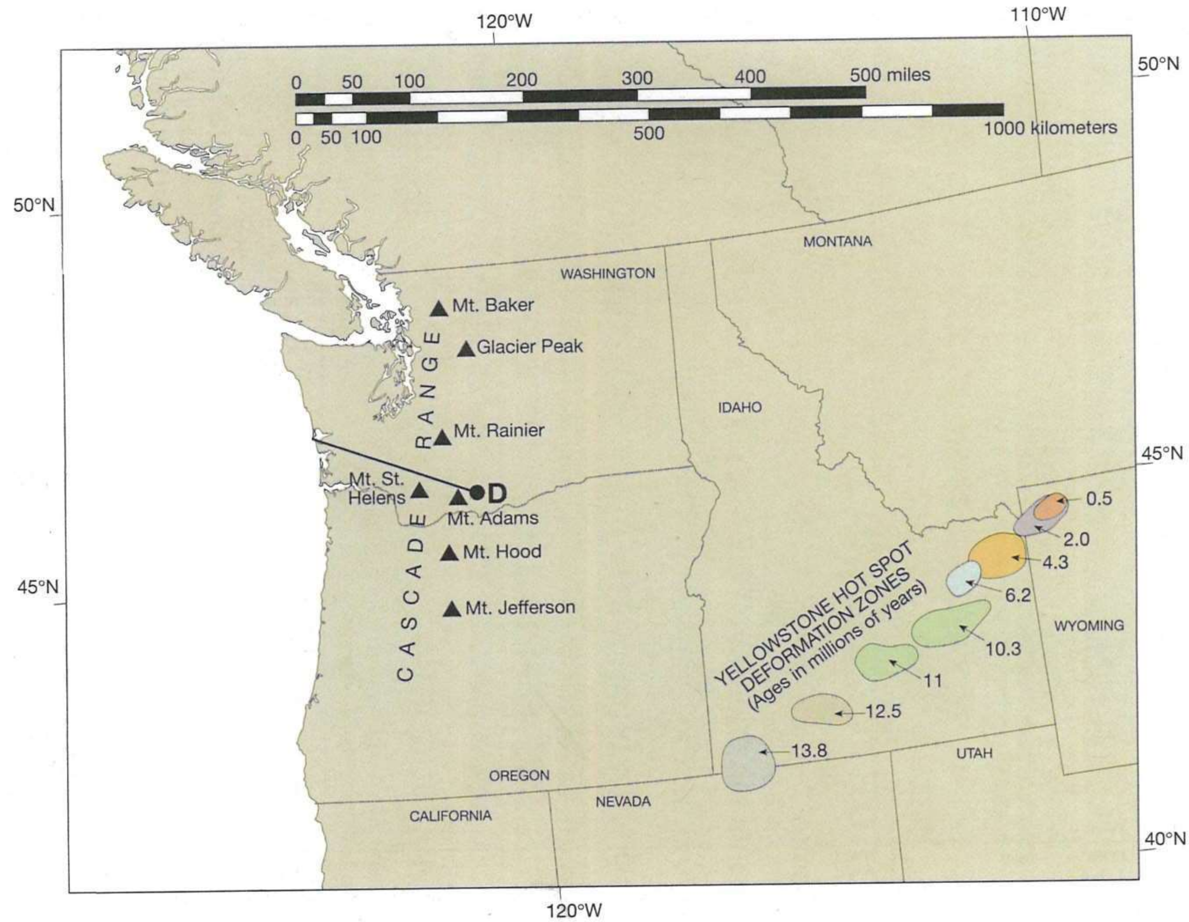


FIGURE 3.9 TRACK OF THE YELLOWSTONE HOT SPOT

NOTES

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Lab 4—Geologic timescales, stratigraphy, and dating rocks

FIGURE 4.1 ZABRISKIE POINT, DEATH VALLEY NATIONAL PARK (BOSCH, 2017)

AGE OF THE EARTH

“So far scientists have not found a way to determine the exact age of the Earth directly from Earth rocks because Earth's oldest rocks have been recycled and destroyed by the process of plate tectonics. If there are any of Earth's primordial rocks left in their original state, they have not yet been found. Nevertheless, scientists have been able to determine the probable age of the Solar System and to calculate an age for the Earth by assuming that the Earth and the rest of the solid bodies in the Solar System formed at the same time and are, therefore, of the same age.

“The ages of Earth and Moon rocks and of meteorites are measured by the decay of long-lived radioactive isotopes of elements that occur naturally in rocks and minerals and that decay with half lives of 700 million to more than 100 billion years to stable isotopes of other elements.
These dating techniques, which are firmly grounded in physics and are known collectively as radiometric dating, are used to measure the last time that the rock being dated was either melted or disturbed sufficiently to rehomogenize its radioactive elements.

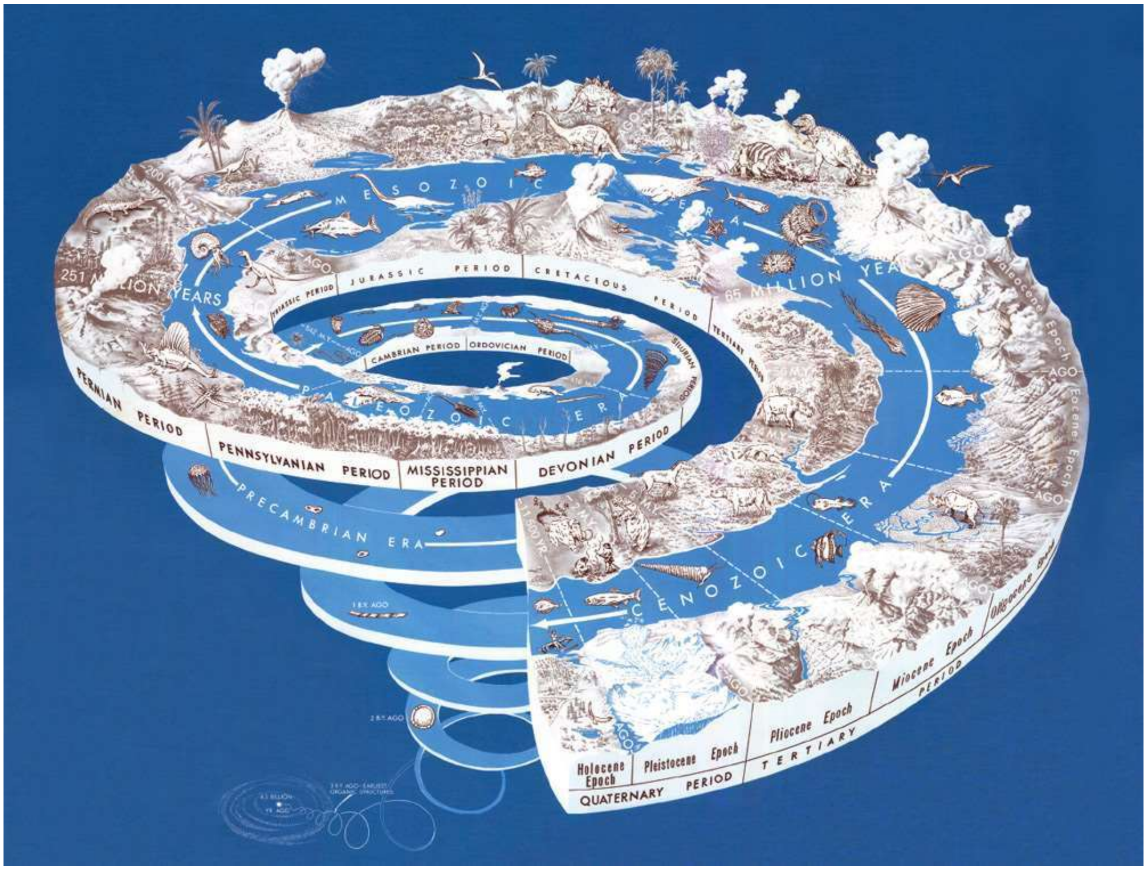


FIGURE 4.2 SPIRAL REPRESENTATION OF THE AGE OF THE EARTH (USGS, 2008)

"Ancient rocks exceeding 3.5 billion years in age are found on all of Earth's continents. The oldest rocks on Earth found so far are the Acasta Gneisses in northwestern Canada near Great Slave Lake (4.03 Ga) and the Isua Supracrustal rocks in West Greenland (3.7 to 3.8 Ga), but well-studied rocks nearly as old are also found in the Minnesota River Valley and northern Michigan (3.5-3.7 billion years), in Swaziland (3.4-3.5 billion years), and in Western Australia (3.4-3.6 billion years). These ancient rocks have been dated by a number of radiometric dating methods and the consistency of the results give scientists confidence that the ages are correct to within a few percent. An interesting feature of these ancient rocks is that they are not from any sort of "primordial crust" but are lava flows and sediments deposited in shallow water, an indication that Earth history began well before these rocks were deposited. In Western Australia, single zircon crystals found in younger sedimentary rocks have radiometric ages of as much as 4.3 billion years, making these tiny crystals the oldest materials to be found on Earth so far. The source rocks for these zircon crystals have not yet been found. The ages measured for Earth's oldest rocks and oldest crystals show that the Earth is at least 4.3 billion years in age but do not reveal the exact age of Earth's formation. The best age for the Earth (4.54 Ga) is based on old, presumed single-stage leads coupled with the Pb ratios in troilite from iron meteorites, specifically the Canyon Diablo meteorite. In addition, mineral grains (zircon) with U-Pb ages of 4.3 Ga have recently been reported from sedimentary rocks in west-central Australia.

“The Moon is more primitive than Earth because it has not been disturbed by plate tectonics; thus, some of its more ancient rocks are more plentiful. Only a small number of rocks were returned to Earth by the six Apollo and three Luna missions. These rocks vary greatly in age, a reflection of their different ages of formation and their subsequent histories. The oldest dated moon rocks, however, have ages between 4.4 and 4.5 billion years and provide a minimum age for the formation of our nearest planetary neighbor. Thousands of meteorites, which are fragments of asteroids that fall to Earth, have been recovered. These primitive objects provide the best ages for the time of formation of the Solar System. There are more than 70 meteorites, of different types, whose ages have been measured using radiometric dating techniques. The results show that the meteorites, and therefore the Solar System, formed between 4.53 and 4.58 billion years ago. The best age for the Earth comes not from dating individual rocks but by considering the Earth and meteorites as part of the same evolving system in which the isotopic composition of lead, specifically the ratio of lead-207 to lead-206 changes over time owing to the decay of radioactive uranium-235 and uranium-238, respectively. Scientists have used this approach to determine the time required for the isotopes in the Earth's oldest lead ores, of which there are only a few, to evolve from its primordial composition, as measured in uranium-free phases of iron meteorites, to its compositions at the time these lead ores separated from their mantle reservoirs. These calculations result in an age for the Earth and meteorites, and hence the Solar System, of *4.54 billion years* with an uncertainty of less than 1 percent. To be precise, this age represents the last time that lead isotopes were homogeneous throughout the inner Solar System and the time that lead and uranium was incorporated into the solid bodies of the Solar System.

“The age of 4.54 billion years found for the Solar System and Earth is consistent with current calculations of 11 to 13 billion years for the age of the Milky Way Galaxy (based on the stage of evolution of globular cluster stars) and the age of 10 to 15 billion years for the age of the Universe (based on the recession of distant galaxies).”

“For additional information on this subject, see G. Brent Dalrymple's *The Age of the Earth*, published by the Stanford University Press (Stanford, Calif.) in 1991 (492 p.). (Dalrymple, 2007)”

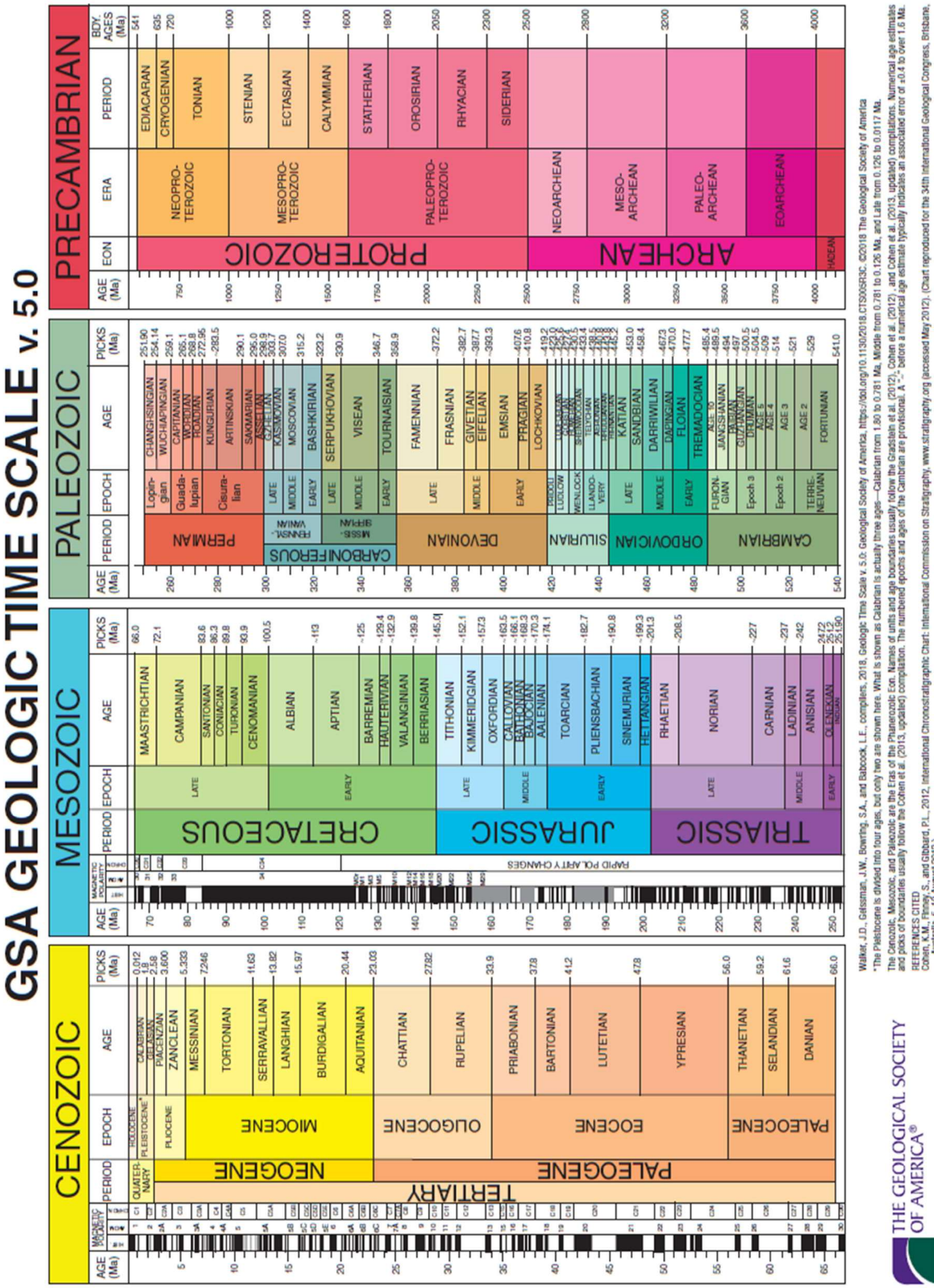


FIGURE 4.3 GEOLOGICAL TIME SCALE

PRINCIPLES OF STRATIGRAPHY

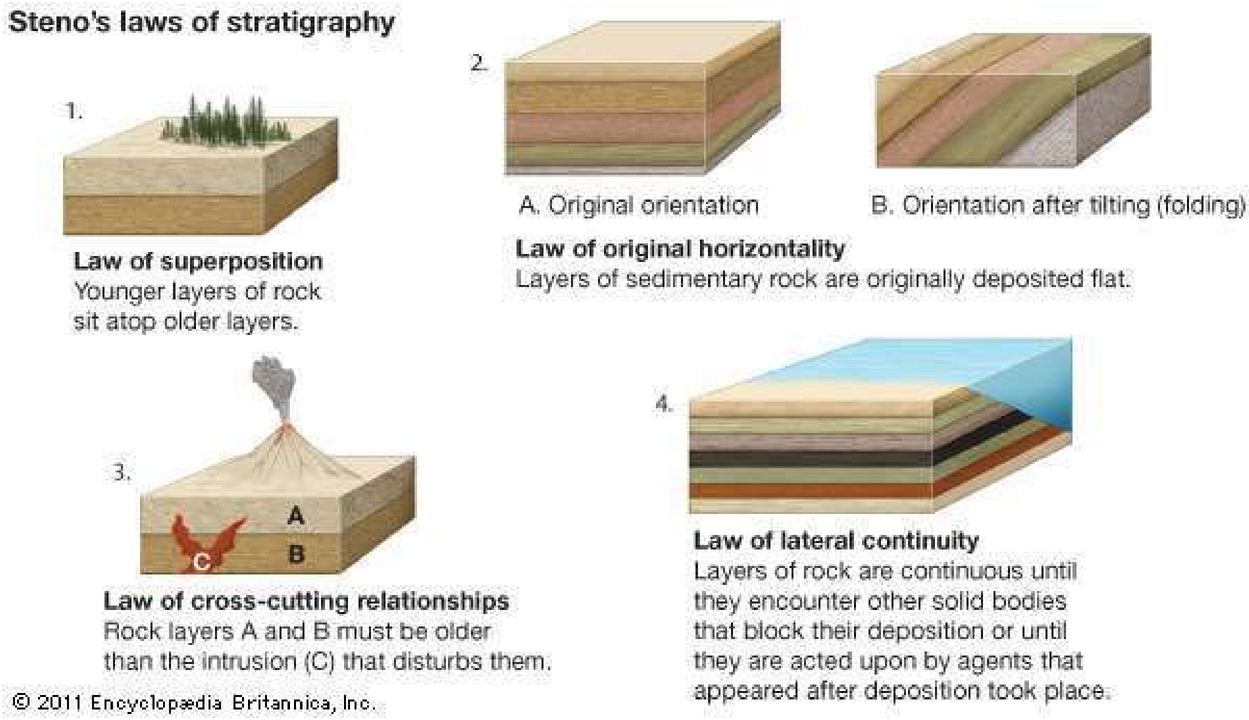


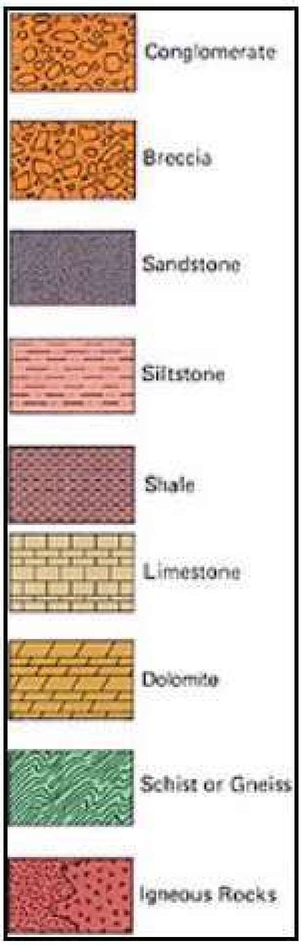
FIGURE 4.4 ILLUSTRATION OF FOUR BASIC LAWS OF STRATIGRAPHIC INTERPRETATION

Nicolaus Steno, in his *Dissertationis prodromus* of 1669 is credited with four of the defining principles of the science of stratigraphy. His words, translated into English by Winter (1916), were:

1. the law of superposition: At the time when a given stratum was being formed, there was beneath it another substance which prevented the further descent of the comminuted matter and so at the time when the lowest stratum was being formed either another solid substance was beneath it, or if some fluid existed there, then it was not only of a different character from the upper fluid, but also heavier than the solid sediment of the upper fluid."
2. the principle of original horizontality: "At the time when one of the upper strata was being formed, the lower stratum had already gained the consistency of a solid."
3. the principle of lateral continuity: "At the time when any given stratum was being formed it was either encompassed on its sides by another solid substance, or it covered the entire spherical surface of the earth. Hence it follows that in whatever place the bared sides of the strata are seen, either a continuation of the same strata must be sought, or another solid substance must be found which kept the matter of the strata from dispersion."
4. the principle of cross-cutting relationships: "At the time when any given stratum was being formed, all the matter resting upon it was fluid, and, therefore, at the time when the lowest stratum was being formed, none of the upper strata existed."

WHAT ARE STRATIGRAPHIC COLUMNS?

Stratigraphic columns are the traditional means of presenting measured geologic sequences as a figure. Information should be arranged with the youngest rock unit at the top and the oldest rock unit at the bottom. The column should consist of small boxes containing the symbol used on the map to identify the rock unit, and if the map is colored or if patterns are used, they should also appear in the box. The name of the rock unit is written adjacent to the box. Brief descriptions of the units may be lettered to the right of the column, as in the figure, or the column may be accompanied by an explanation consisting of a small box for each lithologic symbol and for the other symbols alongside the column. Columns are constructed from the stratigraphic base upward and should be plotted first in pencil in order to insure spaces for gaps at faults and unconformities. Sections that are thicker than the height of the plate can be broken into two or more segments, with the stratigraphic base at the lower left and the top at the upper right. Bedding and unit boundaries are drawn horizontally, except in detailed sections or generalized sections of distinctly nontabular deposits, some gravels, and volcanic units.



The following elements of a stratigraphic column are essential and are generally keyed to the figure:

(1) title, indicating topic, general location, and whether the section is single (measured in one coherent course), composite (pieced from two or more section segments), averaged, or generalized;
(2) name(s) of geologist(s) and date of the survey;
(3) method of measurement;
(4) graphic scale;
(5) map or description of locality;
(6) major chronostratigraphic units, if known;
(7) lesser chronostratigraphic units, if known;
(8) names and boundaries of rock units;
(9) graphic column composed of standard lithologic patterns;
(10) unconformities;
(11) faults, with thick ness of tectonic gaps, if known;
(12) covered intervals, as measured,
(13) positions of key beds; and
(14) positions of important samples with number and perhaps data. Other kinds of information may be included also. (Link et al., 2019)

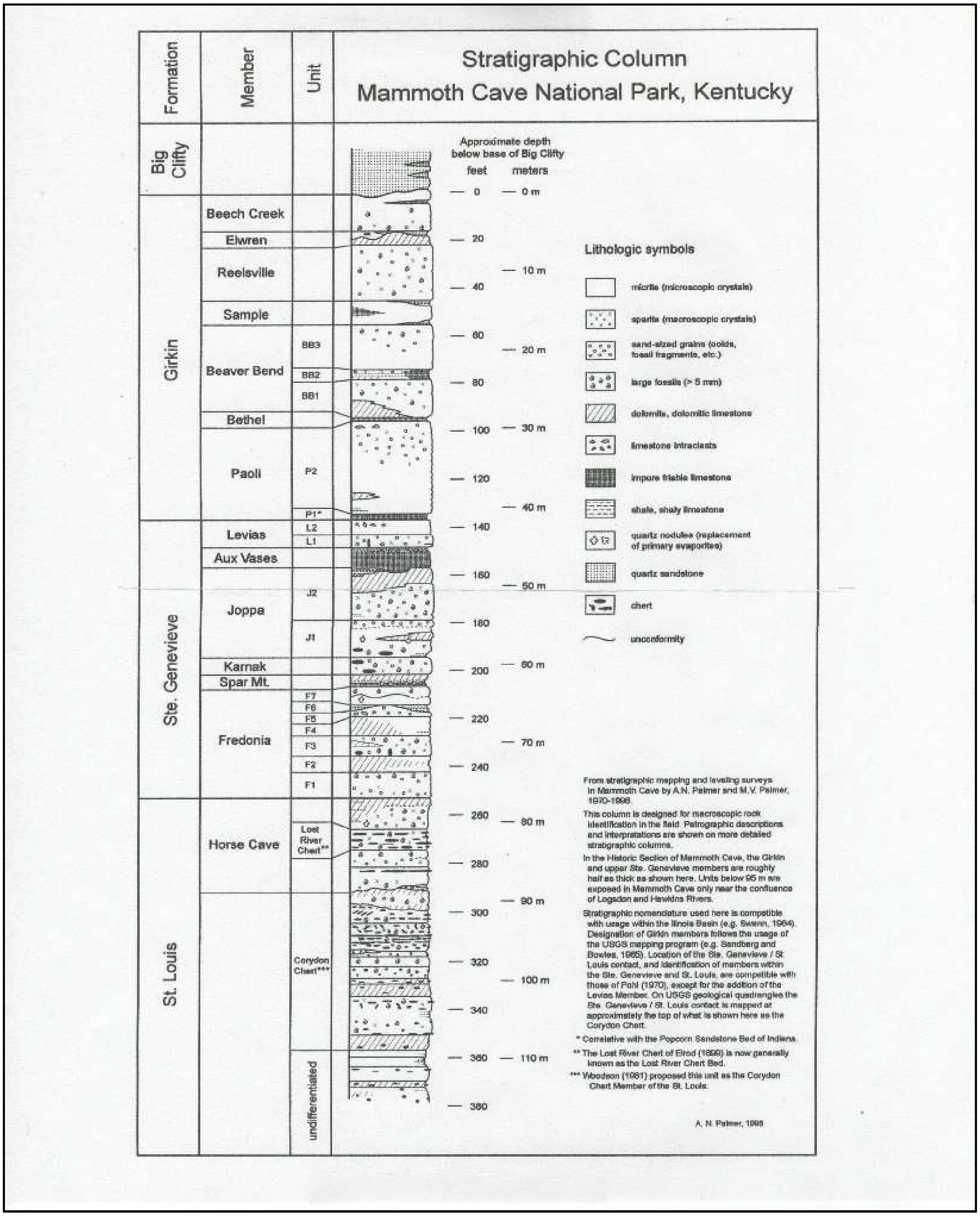


FIGURE 4.5 STRATIGRAPHIC COLUMN, MAMMOTH CAVE NATIONAL PARK, KENTUCKY (PALMER, 1998)

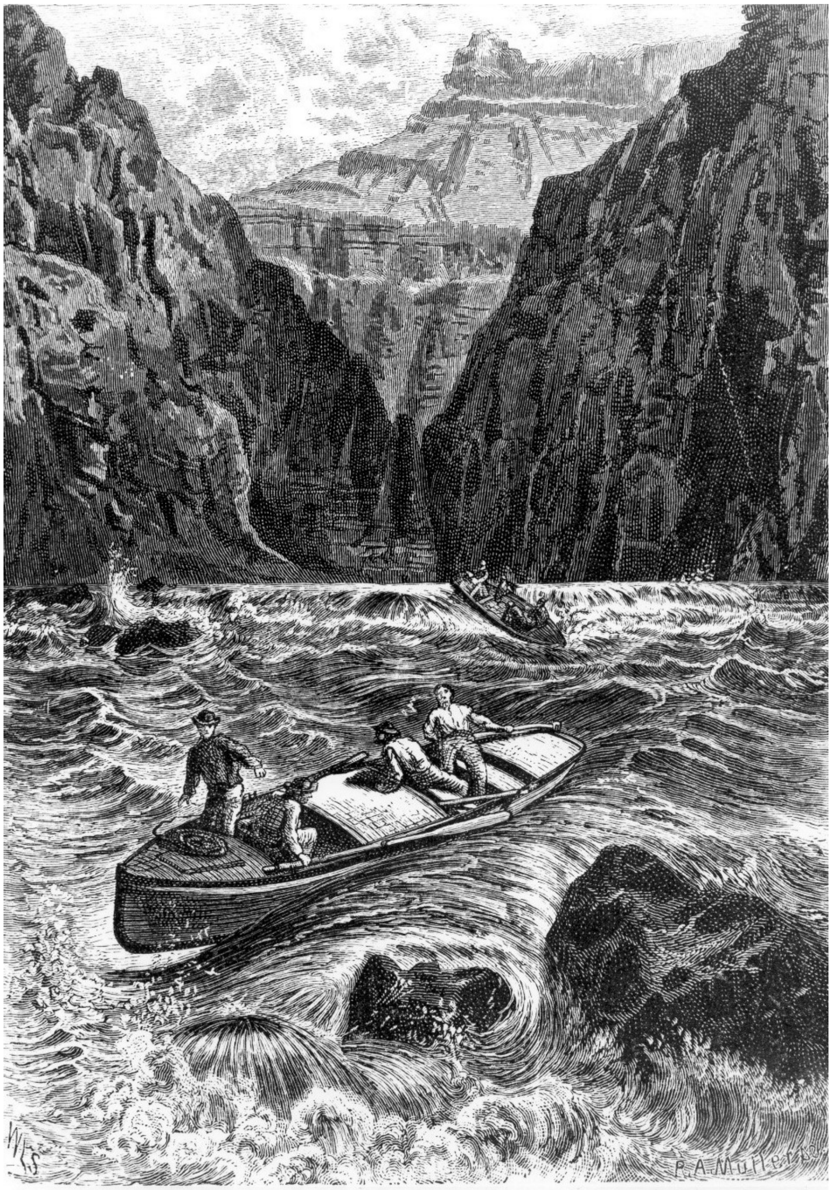
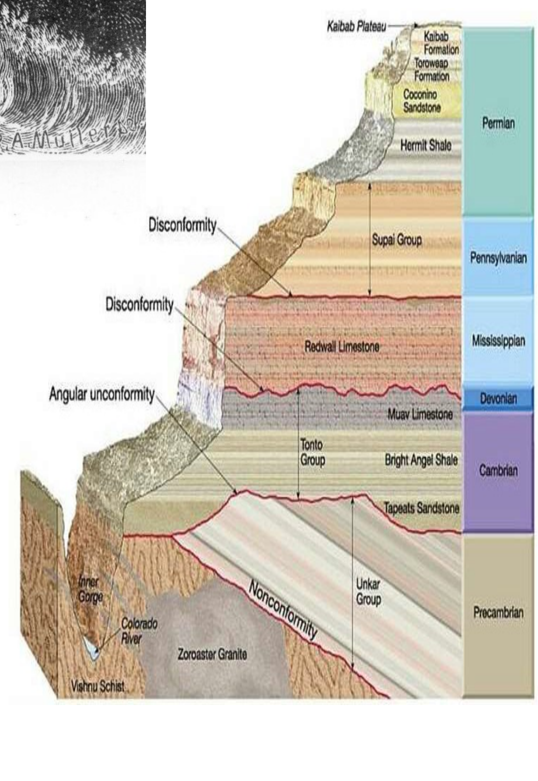


Figure 28.—Running a rapid.

Figure 4.6 (left) "Running a Rapid" engraving made by R.A. Muller (1873) to illustrate the second John Wesley Powell expedition through The Grand Canyon (Image credit, U. S. National Park Service). (below) Stratigraphic column of the sequence of rocks in The Grand Canyon.



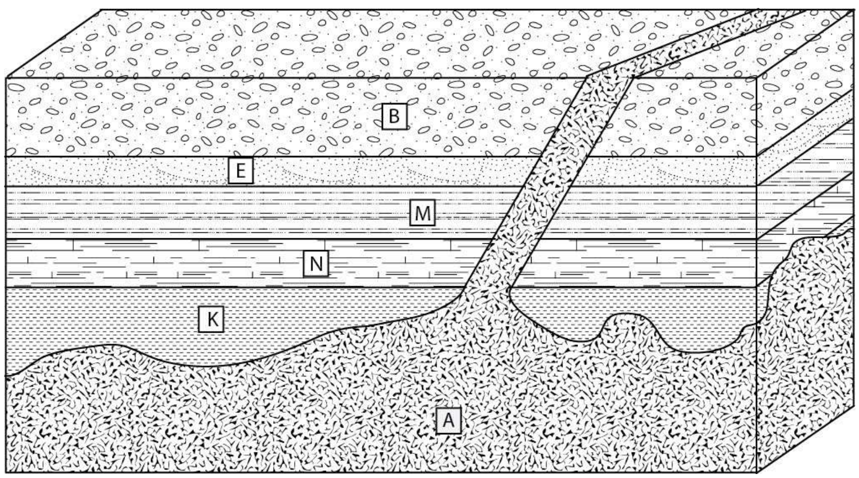
Activity 4.A—to be completed as homework before class:
A Deeper Dive into Deep Time

Download the "Deep Time Walk" app to your smartphone or other portable device. You can learn more about it at the Deep Time Walk website: https://www.deeptimewalk.org/. Then, on your own, or with friend(s), go outside, or to the track in the campus rec center, or someplace else you can walk for a while. Launch the app and follow the directions.

***Note**: This portion of the lab entails walking about 5 kilometers. If you are unable to do this please contact your instructor for an alternate activity.*

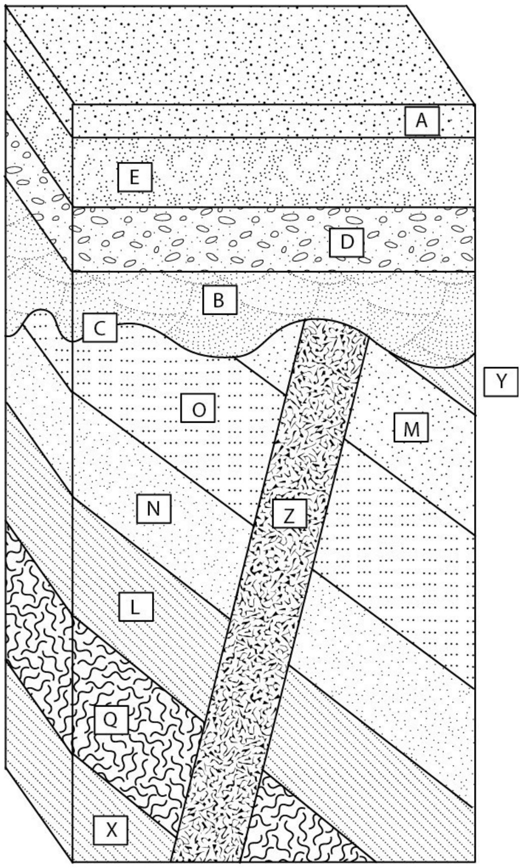
You may want to take notes or otherwise keep track of your reflections so you can incorporate concepts about the scope of geological time into your lab write up.

Activity 4.B: Applying Principles of Stratigraphy



1. List the events in order from oldest to youngest.

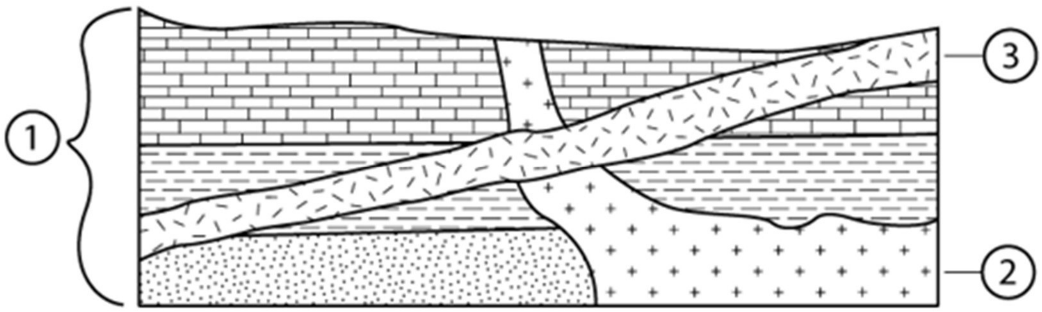
2. What principle allows us to determine the age relationship between Unit N and Unit A?

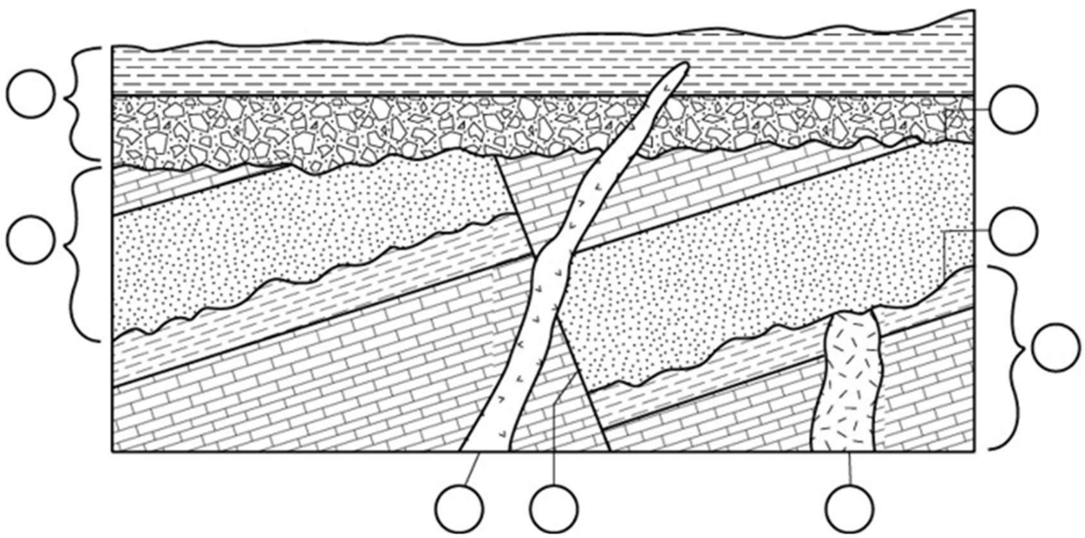


3. List the events in order from oldest to youngest.

4. What principle did you use to determine the age relationship between unit X and unit Q? What about unit B and unit D?

5. Indicate the sequence of events for this problem by adding numbers to the circles as in the example below, letting “1” represent the oldest event.

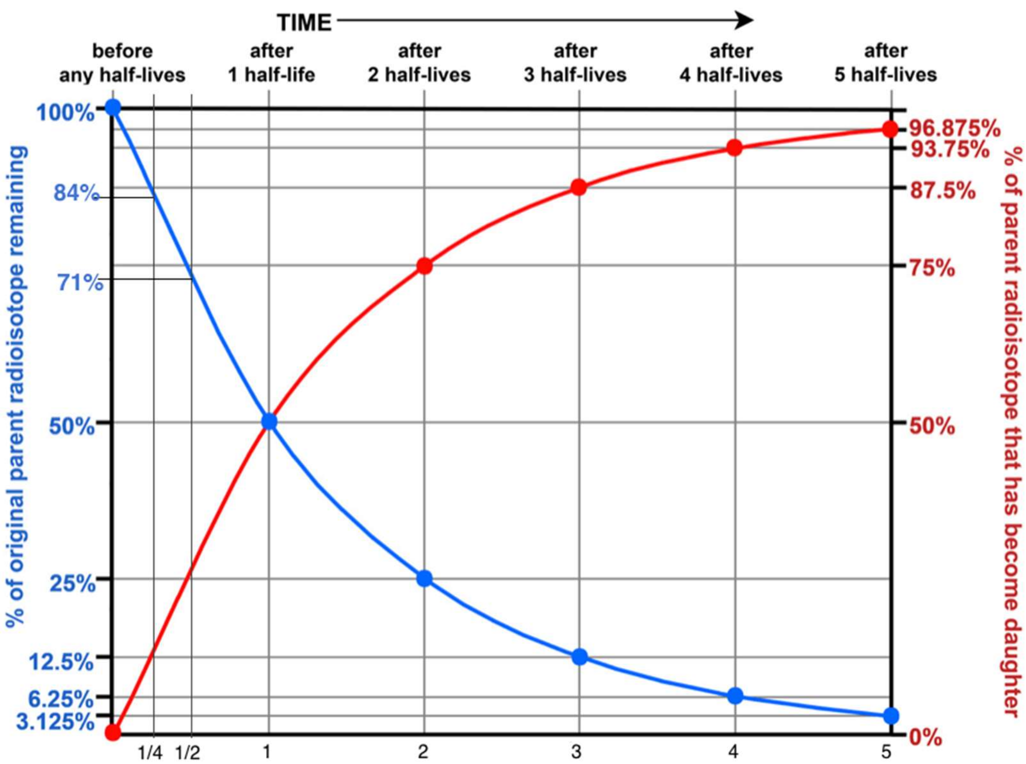




Write a narrative for the sequence of events you labeled above.

Activity 4.C: Radiometric Dating of Rocks (Johnson, 2018)

The blue line and numbers on the y-axis on the graph below shows the % of parent isotopes remaining in a sample. The red line and numbers show the % of daughter isotopes in the sample. The x-axis indicates how many half-lives have passed. The chart below the graph provides the half-lives for some important isotopes.



Parent Isotope	Half-Life	Daughter Isotope
Carbon-14	5,730 years	Nitrogen-14
Uranium-235	713 million years	Lead-207
Potassium-40	1.3 billion years	Argon-40
Uranium-238	4.5 billion years	Lead-206

1. If your sample of potassium feldspar contains 50% argon-40 and 50% potassium-40, how many half lives have passed? ______ and this means your sample is how old?________________

2. If your sample contains 75% argon-40 and 25% potassium-40, how many half lives have passed? ______ and this means your sample is how old?________________

3. How old is your sample if it contains 87.5% Argon?

4. How old is your sample if it contains 84% Potassium?

5. A lava flow containing zircon mineral crystals is exposed in an outcrop in Hawaii. A mass spectrometer analysis showed that 71% of the atoms were Uranium-235 and 29% of the atoms were Lead-207.
    a. What is the half life of Uranium-235?

    b. What is the daughter atom produced when Uranium-235 decays?

    c. How many half-lives of the Uranium-235 Lead-207 decay pair have elapsed?

    d. What is the radiometric age of the lava flow? Show your work.

    e. Are the layers below the lava flow older or younger than the lava flow?

6. Carbon-14 is continuously replaced in living organisms as long as they live. When an organism dies, the Carbon-14 in its body is no longer replaced. Carbon-14 decays to Nitrogen-14, so the amount of Carbon-14 in the dead organism decreases over time.
    a. You are coring into a coral reef to see how old it is. Your coral sample reveals that it has 525 parts of Carbon-14 and 3500 parts of Nitrogen-14. What is the percentage of Carbon-14 in the sample?

b. How old is the coral sample?

7. Layers of sand on a beach in California contain mineral crystals of zircon. Can the zircon crystals be used to date when they were deposited on the beach? Why or why not?

8. When sampling from an ancient peat bog, you must be careful not to include any living roots. Why?

9. All of the rocky material in the solar system, including the Earth, Mercury, Venus, Mars, and the oldest meteorites were formed about the same time. The oldest meteorites found on earth contain equal amounts of Uranium-238 and Lead-206. How old does this make the Earth?

NOTES

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Lab 5—Igneous rocks

WHAT ARE IGNEOUS ROCKS?

"Igneous rocks (from the Greek word for fire) form when hot, molten rock crystallizes and solidifies. The melt originates deep within the Earth near active plate boundaries or hot spots, then rises toward the surface. Igneous rocks are divided into two groups, intrusive or extrusive, depending upon where the molten rock solidifies.

"Intrusive Igneous Rocks:

Intrusive, or plutonic, igneous rock forms when magma is trapped deep inside the Earth. Great globs of molten rock rise toward the surface. Some of the magma may feed volcanoes on the Earth's surface, but most remains trapped below, where it cools very slowly over many thousands or millions of years until it solidifies. Slow cooling means the individual mineral grains have a very long time to grow, so they grow to a relatively large size. Intrusive rocks have a coarse-grained texture.

"Extrusive Igneous Rocks:

Extrusive, or volcanic, igneous rock is produced when magma exits and cools above (or very near) the Earth's surface. These are the rocks that form at erupting volcanoes and oozing fissures. The magma, called lava when molten rock erupts on the surface, cools and solidifies almost instantly when it is exposed to the relatively cool temperature of the atmosphere. Quick cooling means that mineral crystals don't have much time to grow, so these rocks have a very fine-grained or even glassy texture. Hot gas bubbles are often trapped in the quenched lava, forming a bubbly, vesicular texture." (USGS, 2019a)

TEXTURAL TERMS

(1) ***Pegmatitic***—consisting of very-coarse-grained minerals—usually greater than 1 cm in diameter
(2) ***Phaneritic—***consisting of coarse-grained minerals large enough to be identified without the use of a hand lens (larger than 1 mm in diameter)
(3) ***Aphanitic***—consisting of fine-grained minerals, mostly too small to be distinguished by the unaided eye (crystals less than 1 mm in diameter).
(4) ***Porphyritic***
   a. *with coarse-grained groundmass*—large crystals (phenocrysts) set in a groundmass (matrix) of finer/smaller grained crystals
   b. *with fine-grained groundmass*—large crystals (phenocrysts) set in a groundmass (matrix) of very fine-grained crystals
(5) ***Vesicular***—filled with "air bubbles" that have formed as gas bubbles try to escape during a quick cooling process
(6) ***Glassy***—no crystals formed because cooling was so fast that the internal structure is disordered
(7) ***Glassy with Vesicles***—no crystals due to a disordered inner structure, but small vesicles ("air-bubbles") present
(8) ***Pyroclastic***—formed from quickly-cooled material ejected from a volcanic vent

BOWEN’S REACTION SERIES

“Within the field of geology, **Bowen's reaction series** is the work of the petrologist, Norman L. Bowen who summarized, based on experiments and observations of natural rocks, the crystallization sequence of typical basaltic magma undergoing fractional crystallization (i.e., crystallization wherein early-formed crystals are removed from the magma by crystal settling, say, leaving behind a liquid of slightly different composition). Bowen's reaction series is able to explain why certain types of minerals tend to be found together while others are almost never associated with one another. He experimented in the early 1900s with powdered rock material that was heated until it melted and then allowed to cool to a target temperature whereupon he observed the types of minerals that formed in the rocks produced. He repeated this process with progressively cooler temperatures and the results he obtained led him to formulate his reaction series which is still accepted today as the idealized progression of minerals produced by cooling basaltic magma that undergoes fractional crystallization. Based upon Bowen's work, one can infer from the minerals present in a rock the relative conditions under which the material had formed.

“The series is broken into two branches, the continuous and the discontinuous (Fig. 5.1). The branch on the right is the continuous. The minerals at the top of the illustration (given aside) are first to crystallize and so the temperature gradient can be read to be from high to low with the high temperature minerals being on the top and the low temperature ones on the bottom. Since the surface of the Earth is a low temperature environment compared to the zones of rock formation, the chart also easily shows the stability of minerals with the ones at bottom being most stable and the ones at top being quickest to weather, known as the Goldich dissolution series. This is because minerals are most stable in the conditions closest to those under which they had formed. Simply put, the high temperature minerals, the first ones to crystallize in a mass of magma, are most unstable at the Earth's surface and quickest to weather because the surface is most different from the conditions under which they were created. On the other hand, the low temperature minerals are much more stable because the conditions at the surface are much more similar to the conditions under which they formed.” (Wikipedia, 2019).

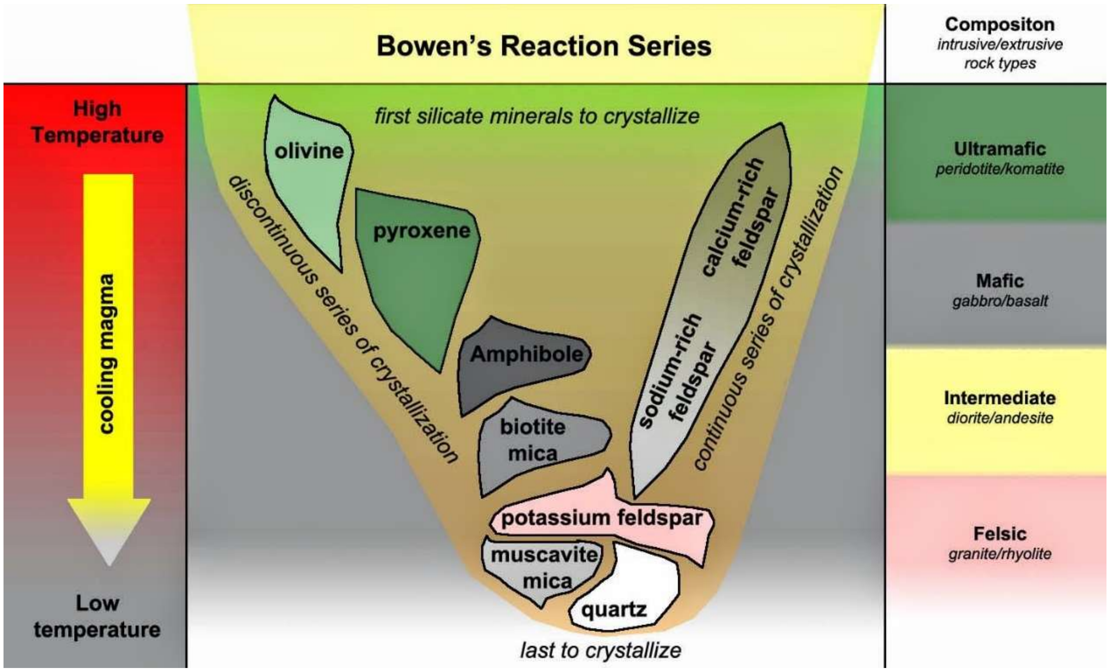


Figure 5.1 Bowen's Reaction Series (Geology In, 2014).

CLASSIFICATION OF IGNEOUS ROCKS

	Felsic	Intermediate	Mafic	Ultramafic
Minerals Present	**Mostly:** Quartz, K-Feldspar, Na-Plagioclase **Some:** biotite, muscovite, and amphibole	**Mostly:** Na-Plagioclase, Ca-plagioclase, amphibole **Some:** biotite	**Mostly:** Ca-plagioclase, pyroxene **Some:** amphibole	**Mostly:** pyroxene and olivine
Phaneritic	**Granite**	**Diorite**	**Gabbro**	**Peridotite**
Porphyritic with coarse-grained groundmass	Porphyritic Granite	Porphyritic Diorite	Porphyritic Gabbro	
Aphanitic	**Rhyolite**	**Andesite**	**Basalt**	
Porphyritic with fine-grained groundmass	Porphyritic Rhyolite	Porphyritic Andesite	Porphyritic Basalt	
Vesicular			Vesicular Basalt	
Glassy	Obsidian			
Glassy with vesicles (more vesicles than rock, very light-weight)	Pumice		Scoria	
Pyroclastic		Tuff		

Sample Number	Texture(s) Present	Composition (Ultramafic, Mafic, Intermediate, Felsic)	Minerals Present and their % Abundance	Rock Name	Inferred Rock Origin/History (cooling rate, Bowens Reaction Series)
1					
2					
3					
4					
5					
6					

Sample Number	Texture(s) Present	Composition (Ultramafic, Mafic, Intermediate, Felsic)	Minerals Present and their % Abundance	Rock Name	Inferred Rock Origin/History (cooling rate, Bowens Reaction Series)
7					
8					
9					
10					
11					
12					
13					

NOTES

Lab 6—Erosion, sedimentation, and sedimentary rocks

WHAT ARE SEDIMENTARY ROCKS?

"Sedimentary rocks are formed from pre-existing rocks or pieces of once-living organisms. They form from deposits that accumulate on the Earth's surface. Sedimentary rocks often have distinctive layering or bedding. Many of the picturesque views of the desert southwest show mesas and arches made of layered sedimentary rock.

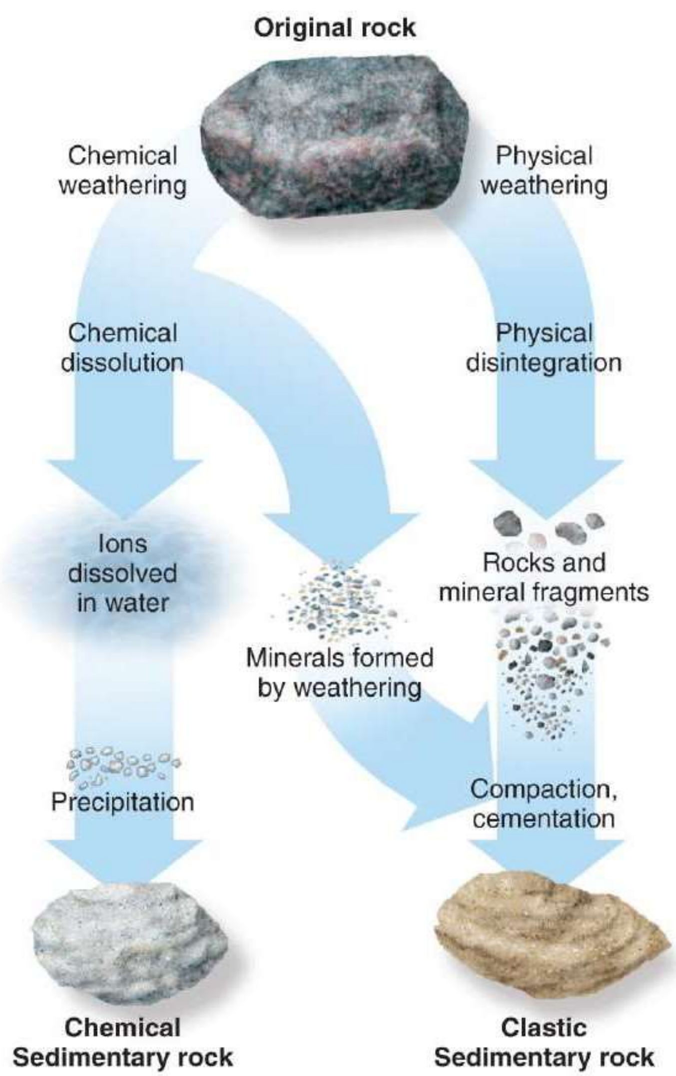
"Common Sedimentary Rocks:

Common sedimentary rocks include sandstone, limestone, and shale. These rocks often start as sediments carried in rivers and deposited in lakes and oceans. When buried, the sediments lose water and become cemented to form rock. Tuffaceous sandstones contain volcanic ash.

"Clastic Sedimentary Rocks:

Clastic sedimentary rocks are the group of rocks most people think of when they think of sedimentary rocks. Clastic sedimentary rocks are made up of pieces (clasts) of pre-existing rocks. Pieces of rock are loosened by weathering, then transported to some basin or depression where sediment is trapped. If the sediment is buried deeply, it becomes compacted and cemented, forming sedimentary rock. Clastic sedimentary rocks may have particles ranging in size from microscopic clay to huge boulders. Their names are based on their clast or grain size. The smallest grains are called clay, then silt, then sand. Grains larger than 2 millimeters are called pebbles. Shale is a rock made mostly of clay, siltstone is made up of silt-sized grains, sandstone is made of sand-sized clasts, and conglomerate is made of pebbles surrounded by a matrix of sand or mud.

"Biologic Sedimentary Rocks: Biologic sedimentary rocks form when large numbers of living things die. Chert is a example for this type of rock, and this is one of the ways limestone can form. Limestone can also form by precipitating out of the water." (USGS, 2019b)



CLASSIFICATION OF SEDIMENTARY ROCKS

Type	Composition	Rock Name
SILICICLASTIC *Formed from broken pieces of weathered rock (clasts).*	rounded cobbles and pebbles (clasts larger than 2 mm), sand, silt, and clay-sized grains	Conglomerate
	angular cobbles, pebbles (clasts larger than 2 mm), sand, silt, and clay	Breccia
	sand-sized grains (clasts between 2 mm and 1/16 mm)	Sandstone
	silt-sized grains (0.004 mm to 1/16 mm)	Siltstone
	mixed silt and clay, blocky pieces with mud-like texture	Mudstone
	clay-sized grains (smaller than 0.004 mm), smooth, breaks into thin chips	Claystone/ shale
CARBONATE *Composed of carbonate minerals such as calcite and dolomite.*	calcite	Limestone
	calcite with some shell and skeletal fragments	Fossiliferous Limestone
	calcite, almost entirely shell and skeletal fragments	Coquina
	calcite, composed of ooids	Oolitic Limestone
	calcite, micro-skeletal fragments	Chalk
BIOGENIC *Forms as the result of an accumulation of organic material*	densely compacted organic material and plant fragments, typically black in color	Coal
	silica (quartz), composed of microorganisms called diatoms	Chert

Lab Exercise: Sedimentary Rock Identification

Sample Number	Sedimentary Rock Type	Textural and Other Distinctive Properties—Grain Size/Grain Type	Rock Name	Depositional Environment: High or Low Energy? How did the rock form?
1				
2				
3				
4				
5				
6				
7				
8				

Sample Number	Sedimentary Rock Type	Textural and Other Distinctive Properties—Grain Size/Grain Type	Rock Name	Depositional Environment: High or Low Energy? How did the rock form?
9				
10				
11				
12				
13				
14				
15				
16				

NOTES

NOTES

Lab 7—Metamorphism and metamorphic rocks

WHAT ARE METAMORPHIC ROCKS?

“Metamorphic rocks started out as some other type of rock, but have been substantially changed from their original igneous, sedimentary, or earlier metamorphic, form. Metamorphic rocks form when rocks are subjected to high heat, high pressure, hot mineral-rich fluids or, more commonly, some combination of these factors. Conditions like these are found deep within the Earth or where tectonic plates meet.

“Process of Metamorphism:
The process of metamorphism does not melt the rocks, but instead transforms them into denser, more compact rocks. New minerals are created either by rearrangement of mineral components or by reactions with fluids that enter the rocks. Pressure or temperature can even change previously metamorphosed rocks into new types. Metamorphic rocks are often squished, smeared out, and folded. Despite these uncomfortable conditions, metamorphic rocks do not get hot enough to melt, or they would become igneous rocks!

“Common Metamorphic Rocks:
Common metamorphic rocks include phyllite, schist, gneiss, quartzite and marble.

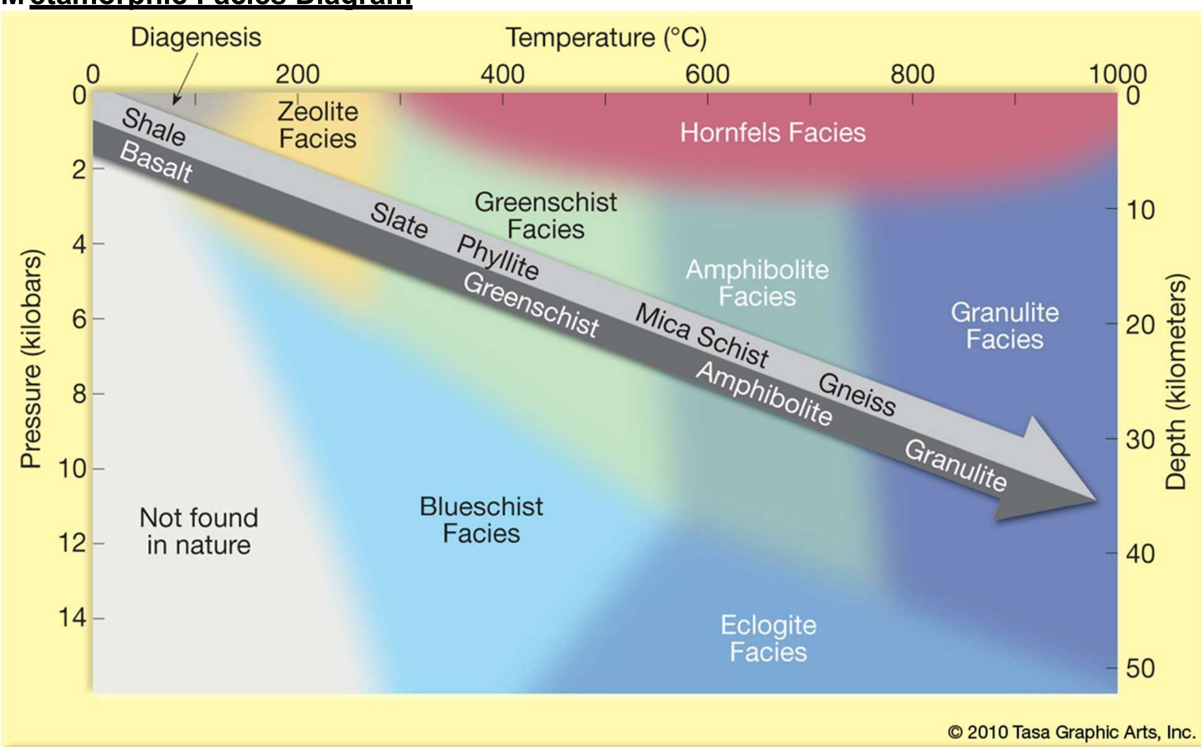
“Foliated Metamorphic Rocks:
Some kinds of metamorphic rocks—granite gneiss and biotite schist are two examples—are strongly banded or foliated. (Foliated means the parallel arrangement of certain mineral grains that gives the rock a striped appearance.) Foliation forms when pressure squeezes the flat or elongate minerals within a rock so they become aligned. These rocks develop a platy or sheet- like structure that reflects the direction that pressure was applied.

“Non-Foliated Metamorphic Rocks:
Non-foliated metamorphic rocks do not have a platy or sheet-like structure. There are several ways that non-foliated rocks can be produced. Some rocks, such as limestone are made of minerals that are not flat or elongate. No matter how much pressure you apply, the grains will not align! Another type of metamorphism, contact metamorphism, occurs when hot igneous rock intrudes into some pre-existing rock. The pre-existing rock is essentially baked by the heat, changing the mineral structure of the rock without addition of pressure.” (USGS, 2019c)

Physical Geology Lab Metamorphic Rock Classification Chart

Texture	Grain Size	Comments	Degree of Metamorphism	Parent Rock	Rock Name
Foliated	Very fine	Strong appearance of layering, smooth dull surfaces	Low	Shale, Mudstone, or Siltstone	**Slate**
	Fine	Breaks along wavey surfaces, glossy sheen	Intermediate Low	Slate	**Phyllite**
	Medium to Coarse	Large flakes of micas (biotite and muscovite) very common	Intermediate High	Phyllite	**Schist**
	Medium to Coarse	Compositional banding due to segregation of minerals	High	Schist, Granite, or Volcanic Rocks	**Gneiss**
Non-foliated	Meduim to Coarse	Interlocking calcite or dolomite grains	----------	Limestone or Dolostone	**Marble**
	Medium to coarse	Fused quartz grains, massive, very hard	----------	Sandstone	**Quartzite**

Metamorphic Facies Diagram



PART 1. Exploring metamorphic processes. For the first part of this lab activity, you will explore the responses (strains) of a material to forces (stresses).

1. Use your modeling clay to make three layers of rock. These initially undeformed layers represent a sedimentary parent rock. Impose stress on your rock layers by folding them several times. How do they change? What kind of metamorphic rock does this resemble?

2. Stress this rock further—you can fold it more, compress it, fault it. How has it changed now? Does it resemble a different metamorphic rock?

PART 2. Complete the following chart for each of the metamorphic samples.

Sample	Texture (Foliated or Non-foliated?)	Protolith (Parent rock)	Metamorphic Facies	Rock Name
1				
2				
3				
4				
5				
6				

Sample	Texture (Foliated or Non-foliated?)	Protolith (Parent rock)	Metamorphic Facies	Rock Name
7				
8				
9				
10				
11				

NOTES

Lab 8—Topographic maps

An Introduction to Topographic Maps

by Dr. David Kendrick, Hobart and William Smith Colleges, Geneva, NY, 2005

To use topographic maps, you need to understand several basic map features:

Maps are fundamental geological tools. We use maps to represent a host of information, including rock distribution, water tables, and, most commonly, the shape of the Earth's surface. **Topography** is the shape of the Earth's surface; maps that represent this surface are called topographic maps. Topographic maps depict the Earth's surface by means of contour lines, or lines of constant elevation.

Goals – your goals in this lab are twofold. 1) Understand how a topographic map represents the Earth's surface and be able to create and interpret such a map. 2) Solve problems using published topographic maps and your newly discovered map-reading abilities.

Location: Location information identifies the area covered by a map. United States Geological Survey (USGS) maps cover rectangular areas and are identified by a quadrangle name. A state index map shows the locations and names of all the quadrangles in a state and can be used to find the quadrangle that covers a particular area. In addition to quadrangle names, USGS maps are marked with latitude and longitude and other coordinate systems that can be used to locate a map area or feature relative to larger geographic features. The latitude and longitude of California, PA is 40.0625N and 79.8953W, respectively.

Map Scale: Maps are scaled-down representations of an area. This means that the distance between two points on a map corresponds to some true distance on the ground. The ratio of map distance to true distance is the map **scale**. Most people are familiar with a map's **scale bar**. A scale bar is a line or bar of some predetermined map length, 2 cm for example, which is labeled with the corresponding true distance, for example, 2 kilometers. Map scales can also be expressed as a ratio or fraction. Many topographic maps, for instance, have a scale of 1:24,000. This means that one cm on the map equals 24,000 cm on the ground, one foot on the map equals 24,000 feet on the ground, *etc.* The scale 1:24,000 can also be expressed as a decimal fraction, 1/24000 =0.000041666. While scale bars are handy for a rough approximation of lengths, fractional scales allow precise calculations of lengths. Two equations are particularly useful:

*True Distance = (Map Distance) * (Fractional Scale) Map Distance =*

(True Distance) / (Fractional Scale)

Note: These expressions assume that map and true distances are expressed in the same units! Thus if you measure map distance in cm and calculate true distance, the calculated distance will be in cm. If true distance is in miles and you calculate map distance, the calculated distance will be in miles.

Orientation: Most maps have a North arrow. When the map is oriented so that the North arrow on the map points to north on the Earth, directions on the map are the same as directions on the ground and the map can be used for navigation. In addition to showing true geographic North, USGS maps show magnetic north. In California, the discrepancy is about 9° west; compass needles point to a direction that is 9° west of due North. This "magnetic declination" changes with location—in the western United States, magnetic declinations are east of due North. Besides North arrows, lines of longitude and latitude or other similar coordinate systems can be used to orient a map.

Contour Lines: Contour lines indicate the shape of the land surface, *i.e.* its topography. A contour line is the map trace of an imaginary line on the ground that has a particular elevation. One way of visualizing such a line is to imagine a shoreline. Bodies of standing water have level upper surfaces, thus their shorelines are traces on the ground surface of that particular elevation. Topographic maps have many contour lines, each adjacent line differing by a constant elevation difference, the **contour interval** (Figure 1).

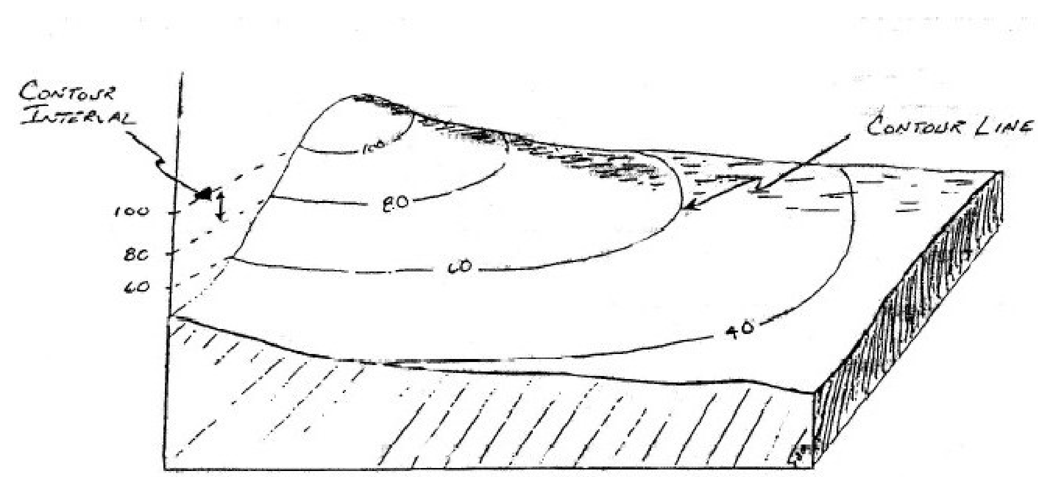


Figure 1: Example of contour lines on a 3-dimensional block diagram.

Contour lines follow some basic rules. If you understand contour lines, you should be able to explain why each of these rules is true:

1. *The closer spaced contour lines are, the steeper the ground surface is.*
2. *Contour lines never cross*
3. *Contour lines never branch*
4. *Contour lines never change elevation*
5. *Contour lines never skip (e.g., you can never have the sequence of lines 10, 20, 40 without having 10, 20, 30, 40)*
6. *Contour lines always have an up side and a down side (all elevations on one side of the line are higher than the line, all elevations on the other side lower). The up and down side never change along the length of the contour line.*

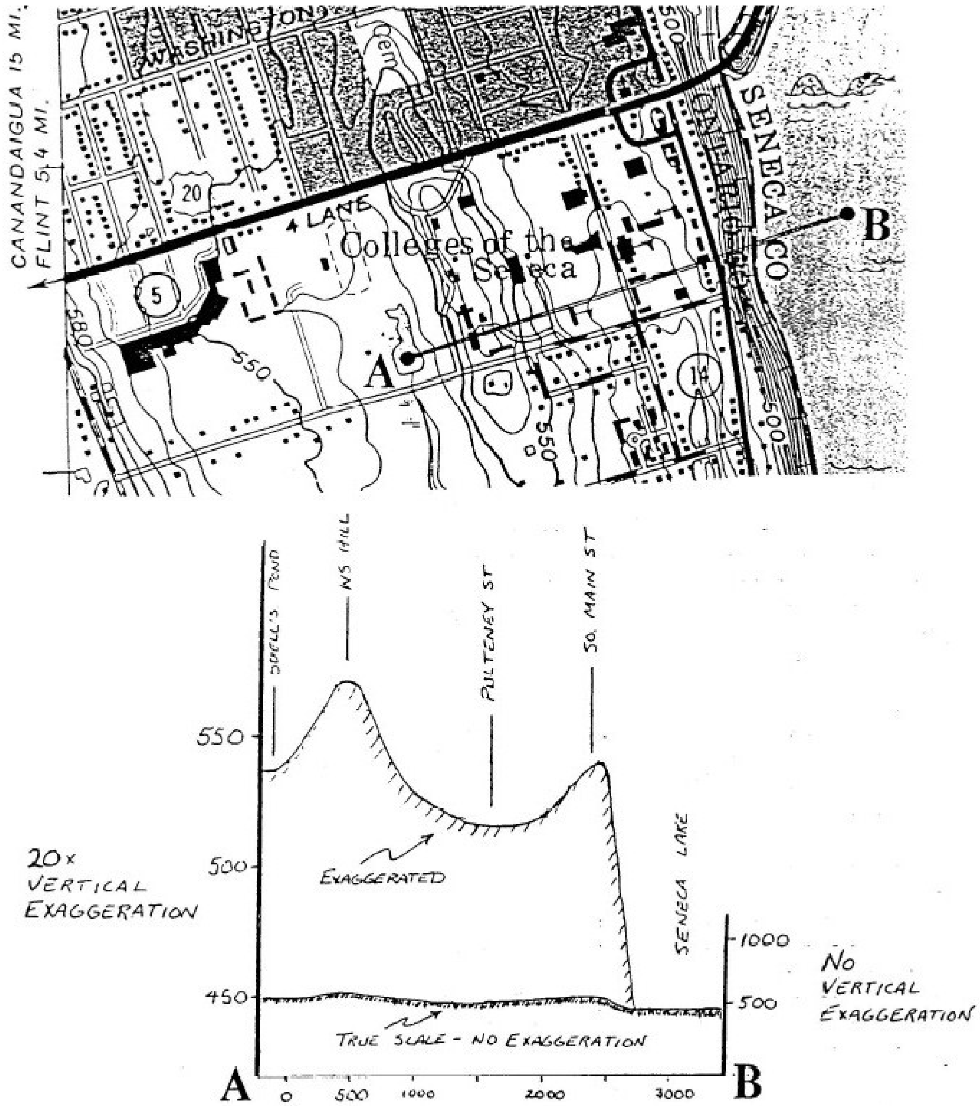
Making a Topographic Profile

Topographic profiles are scaled drawings depicting the elevation of the land surface along some particular line. Figure 2, for example, is a topographic profile that runs EW through the campus of Hobart & William Smith Colleges in Geneva, NY. A drumlin (a glacial landform that appears as a streamlined hill) is bisected by the profile line.

If the vertical scale of the profile is the same as that of the map, the profile has no vertical exaggeration. Often, however, it is advantageous to use a scale that “stretches” or exaggerates the vertical dimension in order to emphasize topographic features. Figure 2 shows both an unexaggerated and an exaggerated profile. The vertical exaggeration can be calculated from the vertical and horizontal scales. If the horizontal scale is 1:1000 and the vertical scale is 1:50, then the vertical exaggeration is 20X.

$$Vertical\ Exaggeration = \frac{Vertical\ Scale}{Horiztonal\ Scale} = \frac{1/50}{1/1000} = 20X$$

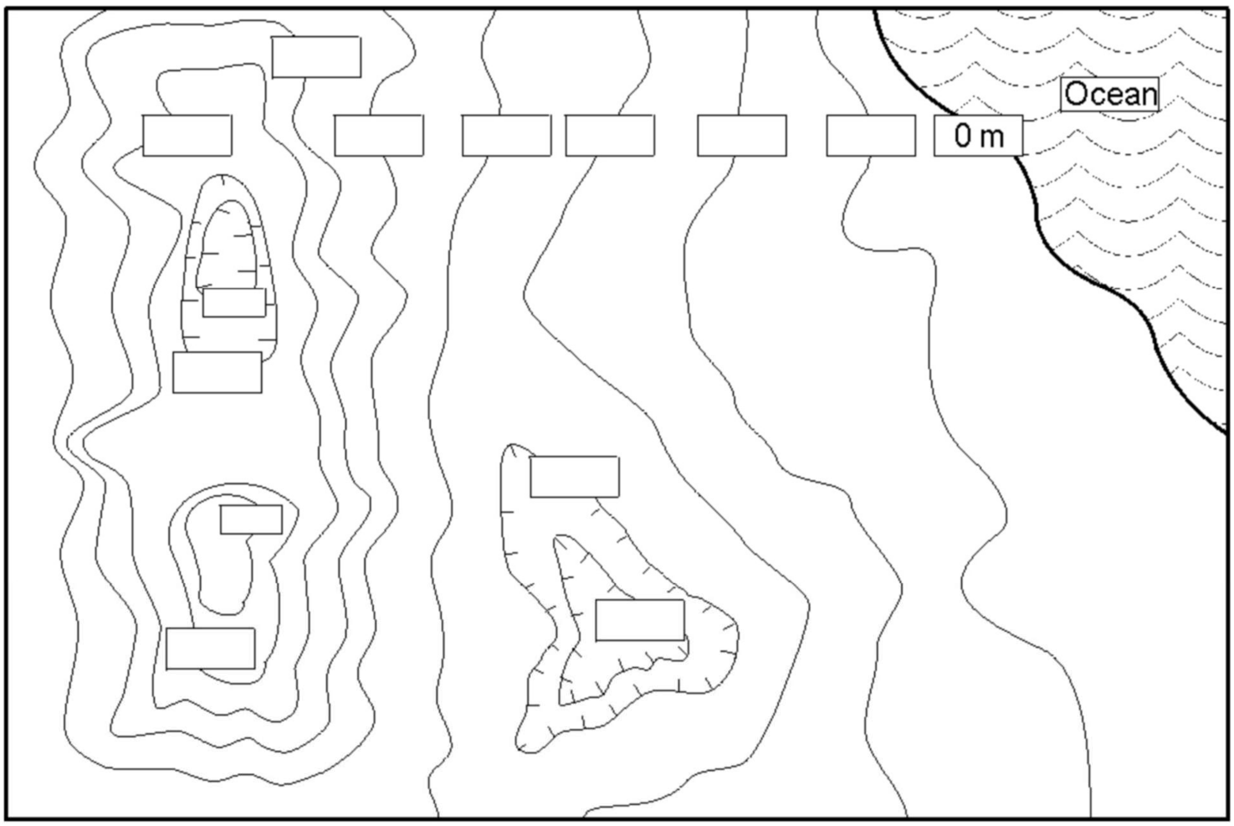
Figure 2: Local area surrounding Hobart and William Smith Colleges, Geneva NY. Note the cross-section line A-B.



LAB 8 – Topographic maps, streams, and drainage basins

Part I: Understanding Topographic Maps

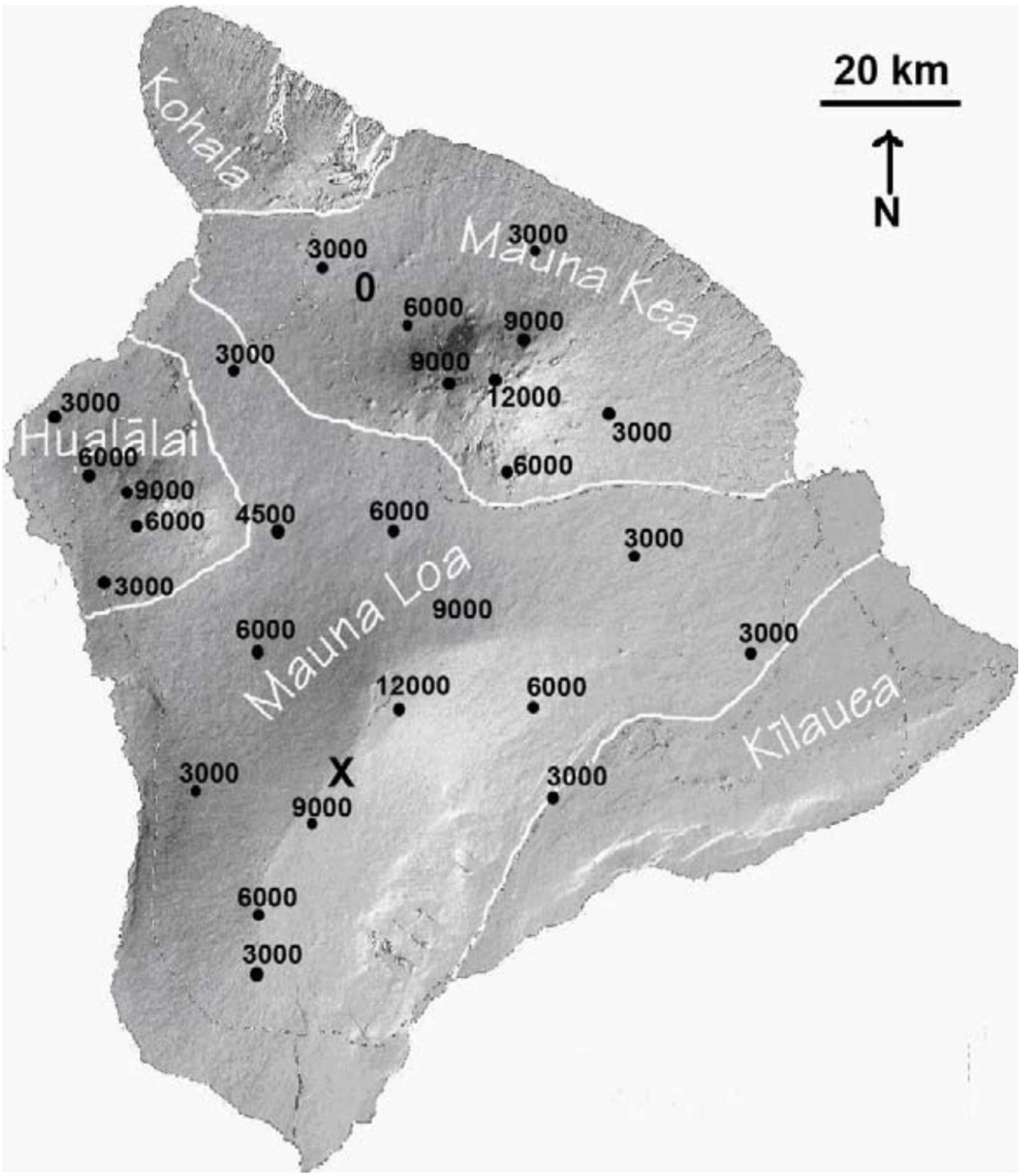
1. Label the elevation of the contours on the map below. Watch out for depressions with repeated contours!



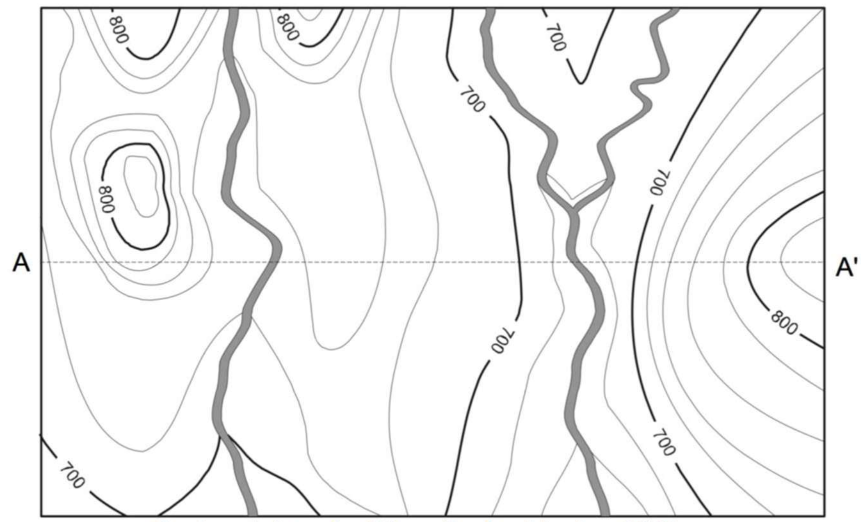
Contour Interval = 20 m

2. The shaded relief map below provides elevation measurements (in feet) across the island of Hawaii, an active volcanic island with two large peaks, Mauna Kea and Mauna Loa. Using a 3000 ft contour interval, draw and label the contour lines across the island. Sea level elevation = 0 ft. Don't forget about the rule of V's! Estimate the elevation of location X by interpolating between the contour lines.

X =______________________ft



3. Using the topographic map below, construct a topographic profile from A to A'. To easily measure distance, fold your paper along the dotted line below the graph and line the crease up with the A to A' profile line (or use a ruler). Grey shaded areas are rivers.



Contour Interval = 20m   Scale: 1 inch = 1000 m

4. On the profile you just created:
   a. What is the horizontal scale in meters/inch?

   b. What is the vertical scale in meters/inch?

   c. What is the vertical exaggeration?

Part II: USGS Topographic Maps

For this section, examine one of the topographic maps provided. All of the information in this section is written somewhere on the map so it should be relatively easy to find.

5. What is the name of this quadrangle?

6. What part of which state is this quadrangle in?

7. Is this a 7 1/2 or a 15 minute quadrangle?

8. What is the difference in area between a 7 1/2 and a 15 minute quadrangle?

9. What is the ratio scale of this map?

10. How many meters in real life does 1 cm on the map equal?

    1 cm on the map =__________meters in real life

11. What is the magnetic declination in the area of this map?

12. If you wanted to hike eastward past the limit of this map, which quadrangle would you need a map of?

13. What is the contour interval of this map? ___

14. What is the INDEX CONTOUR interval of this map? __
15. Where, in general, is the highest elevation in this quadrangle? What is the elevation there?

16. Where, in general, is the lowest elevation in this quadrangle? What is the elevation there?

17. What is the total relief of the map?

Part III: Using topographic maps to measure streams and drainage basins

18. Locate **Map 1** and find its location on the location map page. You are looking at two very small streams in the Mt. Airy region of Cincinnati. These streams are not drawn on the map, but their basins should be labeled ***1*** and ***2***.

19. What larger stream do these two basins contribute to? What river does that stream enter? Where does this water end up when it reaches sea level?

20. Draw an arrow indicating which direction the west fork of Mill Creek is flowing here.

21. Using the contour lines a guide, draw in the stream network in each of the two basins, directly on the map. Follow each stream to where it joins the west fork of Mill Creek.

22. On the map, draw the drainage divides for each of these basins, again using the contours as a guide.

23. On the graph paper below, construct a *longitudinal stream profile* for the main stem (longest) streams in ***basin 1*** and ***basin 2***.

- You will need to plot elevation on the vertical axis vs. stream distance on the horizontal axis. The contour crossings are good places to measure these values.
- Your profiles should both begin where the west fork of Mill Creek exits the map and extend upstream to the drainage divide in each basin.
- You will need to measure distance along the stream with a ruler, and to convert map units to real-world distance. Be sure to label your axes, including units!

24. On the profile you just created:
    a. What is the horizontal scale in meters/inch?

    b. What is the vertical scale in meters/inch?

    c. What is the vertical exaggeration?

25. What differences exist between the elevation profiles of two streams?

26. Are there any changes in slope (stream gradient) visible along the profiles? Describe them.

27. What is the steepest stream gradient present in ***basin 1***? At what elevation is it found?

28. What is the steepest stream gradient present in ***basin 2***? At what elevation is it found?

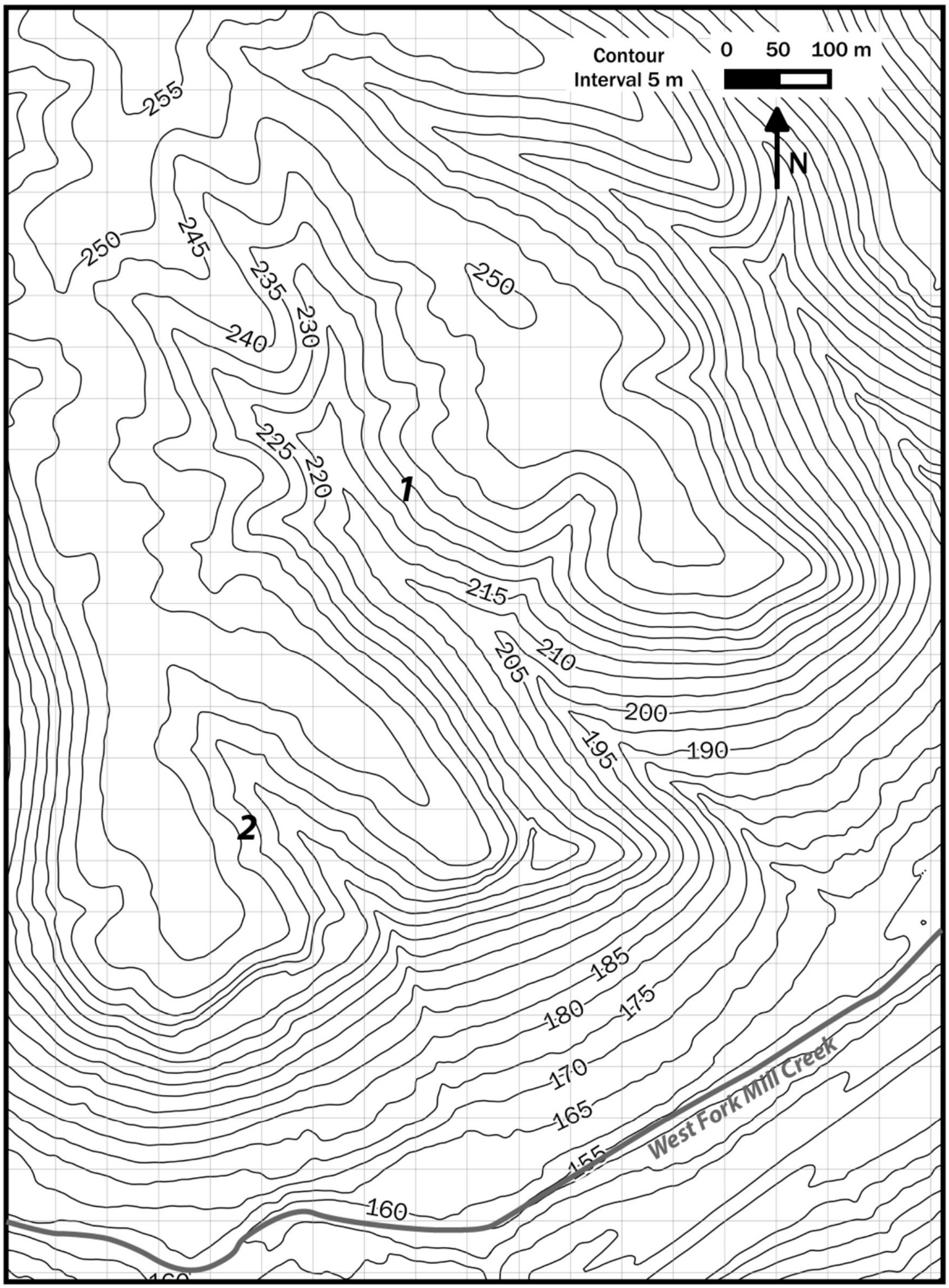
29. Using the drainage basins you delineated, measure the drainage area contributing to each stream above where it joins the west fork of Mill Creek. You can use the grid on the map to estimate the area of the basin (note the grid spacing by comparison to the map scale).

Area of ***basin 1***:______m^2

Area of ***basin 2***:______m^2

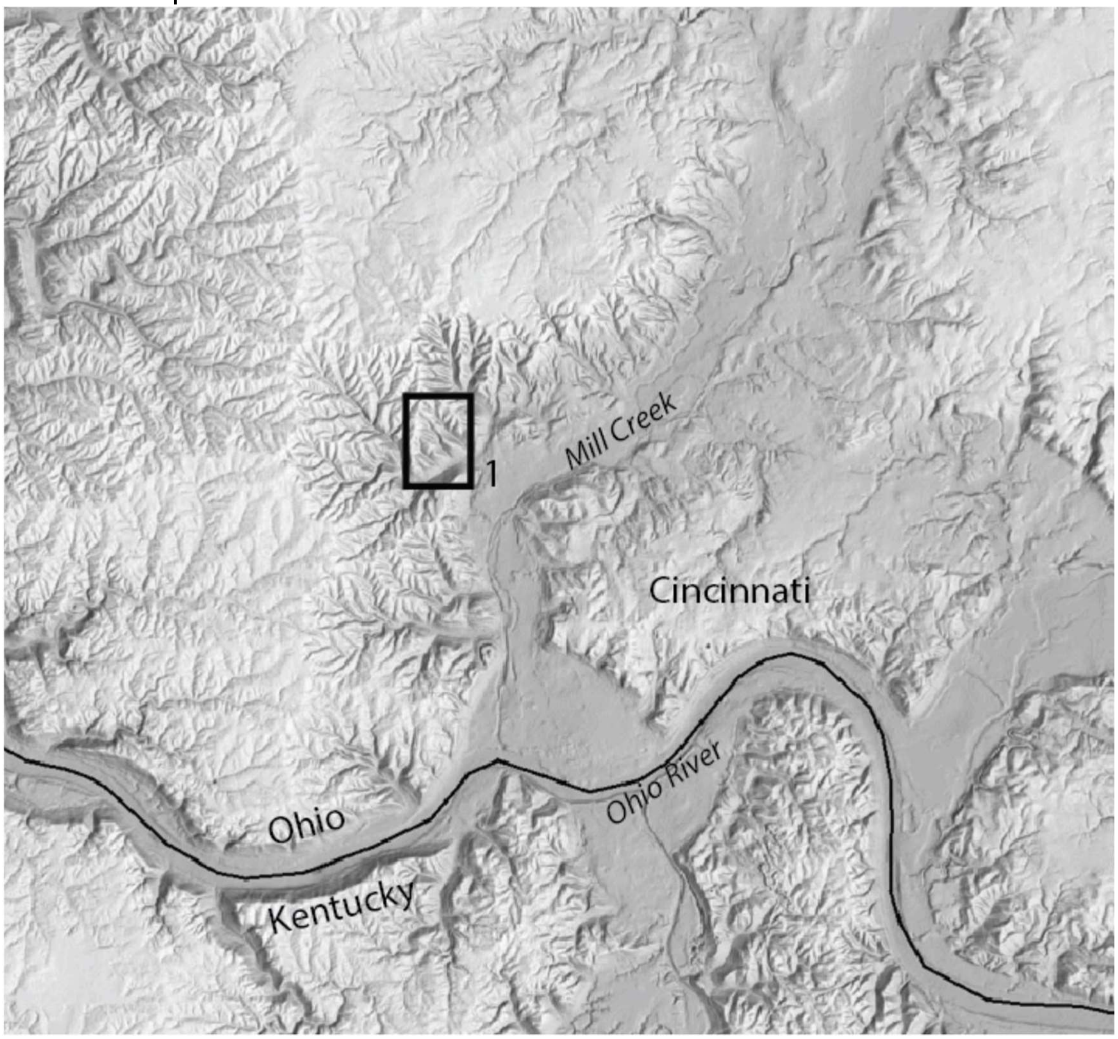
30. Assuming the average rainfall is the same for both drainage basins (which it should be, as they are very close together!), which one would you expect to have a larger stream in it?

31. Given your answer to the previous question, and what you know about streams, develop an explanation for the difference in stream gradient between the two basins.



Map 1. Small creeks in Mt. Airy Forest, Cincinnati.

Location of Map 1.



NOTES

Lab 9—Structural geology

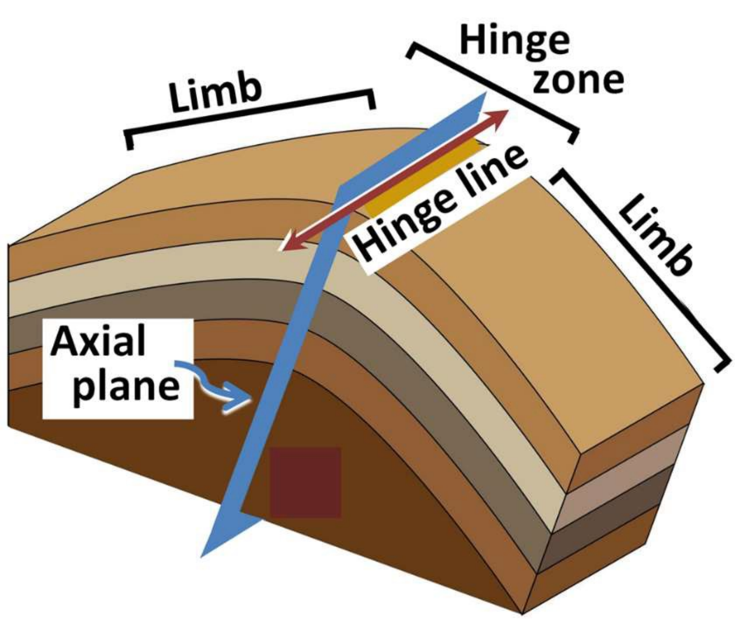
WHAT IS STRUCTURAL GEOLOGY?

Structure geology refers to the subdiscipline within the geosciences that studies the physical responses of the Earth's crust to mechanical forces. The forces that rocks are subject to are referred to as ***stresses***. Depending upon how great the stress is and how rapidly the stress is applied to rocks, they may deform permanently, temporarily, or not at all. This deformation of rocks in response to stress is called ***strain***.

Structural geologists measure the strains exhibited in rocks as geologic structures to understand the stress fields that caused those deformations. This can then help them determine the forces exerted during the tectonic history or other events in the region they are studying.

The structures in rocks that exhibit strain may fall into one of these categories: joints, shear fractures, faults, folds, cleavage, foliations, lineations, or shear zones. When rocks have a ductile response to stress, they fold without breaking. Then the response is brittle, the rocks break, resulting in faulting.

FOLDS AND FAULTS



Types of folds

Anticline—linear axis, oldest rocks in the center of the fold, limbs generally dip away from the hinge

Syncline—linear axis, youngest rocks in the center of the fold, limbs generally dip toward the hinge

Dome—nonlinear, oldest rocks in the center, rocks dip away from the center in all directions

Basin—nonlinear, youngest rocks in the center, rocks dip toward the center in all directions

FIGURE 9.1 PARTS OF A FOLD, USING AN ANTICLINE FOR AN EXAMPLE (OHARE, 2019)

Types of faults

Strike-slip—rocks are displaced along the strike of the strata. Strike-slip faults can be **left lateral** (sinistral) or **right lateral** (dextral). If you were to physically stand on one side of the fault and look at the other, that other side would be displaced to the right or left relative to the side you are standing on. The direction to which it is displaced determines its name. See Fig. 9.2 below for an illustration of strike-slip faults.

FIGURE 9.2 STRIKE-SLIP FAULTS AS SEEN FROM THE TOP, LOOKING DOWN (PLAN OR MAP VIEW). LEFT-LATERAL STRIKE- SLIP FAULT ON THE LEFT, RIGHT-LATERAL STRIKE-SLIP FAULT ON THE RIGHT.

Dip-slip—rocks are displaced along the dip of the strata. Dip-slip faults have a hanging wall above the fault-plane surface and a footwall below the fault -plane surface. In cases where the hanging wall has moved down-dip relative to the position of the footwall, this is called a **normal fault**. In a **reverse** (or thrust) **fault**, the hanging wall has been displaced upward relative to the footwall.

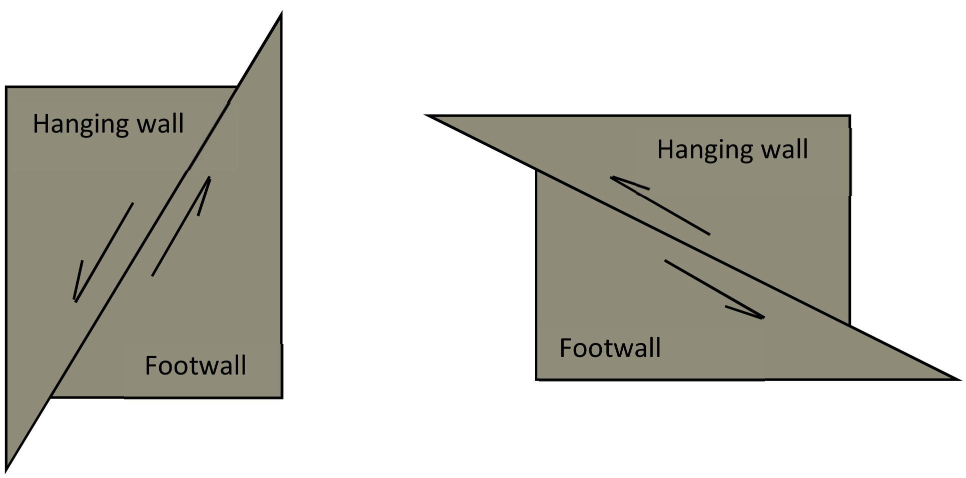


FIGURE 9.3 DIP-SLIP FAULTS AS SEEN FROM THE SIDE (CROSS-SECTION VIEW). NORMAL FAULT ON THE LEFT AND REVERSE FAULT ON THE RIGHT.

Oblique-slip—the displacement of the fault is a combination of strike-slip and dip-slip

HOW DO WE MEASURE GEOLOGIC STRUCTURES?

Two measurements are used in structural geology to indicate the positioning of rock units: **strike** and **dip**. To envision the way strike and dip are defined, you can intersect the geologic unit of interest with an imaginary horizontal plane. The azimuthal (compass-direction) orientation of the intersecting line is the strike direction. The dip direction is perpendicular to the strike direction, and the angle at which the bed slopes down from the horizontal is the dip angle. Figure 9.4 illustrates the relationship between strike and dip on geologic strata and shows how strike and dip are indicated on a map.

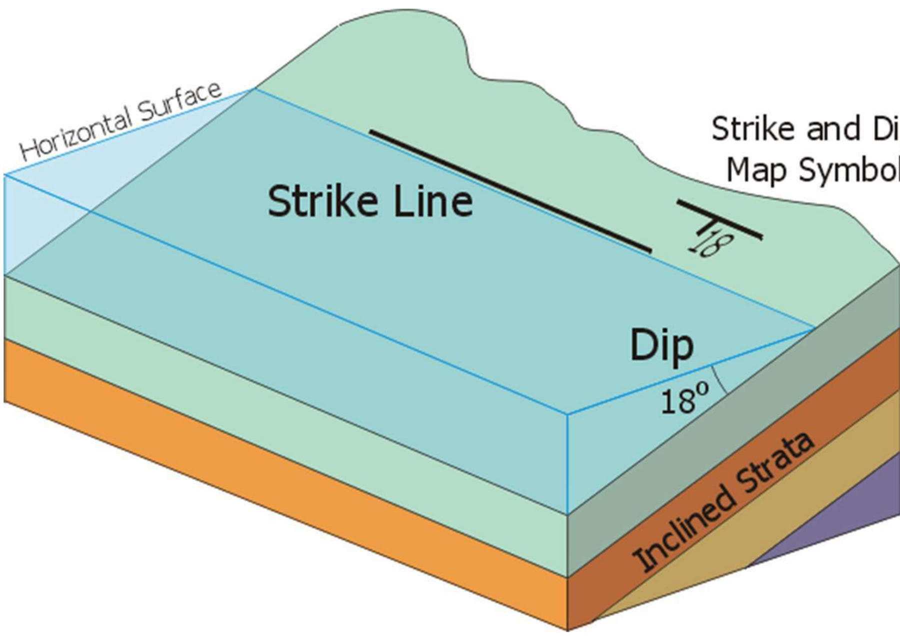
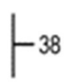
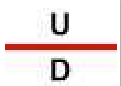
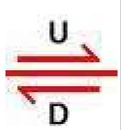


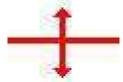
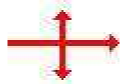
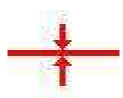
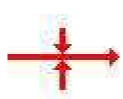
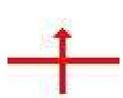
FIGURE 9.4. STRIKE AND DIP ILLUSTRATED (GEOLOGY IN CROSSECTION, 2019).

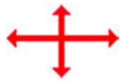
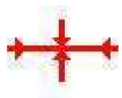
HOW ARE GEOLOGIC STRUCTURES INDICATED ON MAPS?

The following three tables by Dawes and Dawes (2011) summarize many structural symbols that are used on geologic maps.

Strike and Dip Symbols		
Strike and dip are a way of representing the three-dimensional orientation of a planar surface on a two-dimensional map. The strike is the compass direction of a horizontal line on the plane. All the horizontal lines on a plane are parallel, so they all have the same characteristic compass direction. The dip is the angle at which the plane slopes downhill from the horizontal, at its maximum slope, which is at right angles (90ï¿½) from strike.		
Map Symbol	**Definition**	**Explanation of symbol**
	strike and dip of beds other than horizontal or vertical	• strike (longer line) is horizontal line on bedding plane • strike parallels nearby contacts between stratified rocks • dip shows which way beds run downhill • dip angle, number at end of dip symbol, is how much beds tilt down from horizontal
	horizontal beds	• because the bed is horizontal it strikes in all directions • because the bed is horizontal, the dip is 0%
	strike and dip of vertical beds	• strike (longer line) is horizontal line on bedding plane • because the bed dips vertically (has a 90% dip), it dips equally in either direction at right angles to strike, so the dip line is shown extending in both directions

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

Geologic Fold Symbols			
Type of Fold	**Map Symbol**	**Definition**	**Appearance of Beds in Map View**
anticline		up fold	• roughly parallel stripes • dip away from center (away from axis) • oldest at center (along axis) • youngest farthest from center
plunging anticline		up fold with tilted axis	• roughly a U-shaped pattern • plunges in the direction that the U • points • oldest at center (along axis) youngest farthest from center
syncline		down fold	• roughly parallel stripes • dip toward center (toward axis) • oldest farthest from center • youngest at center (along axis)
plunging syncline		down fold with tilted axis	• roughly a U-shaped pattern • plunges in direction U opens • oldest farthest from center • youngest at center (along axis)
monocline		strata tilted in one direction	• all dip in same direction

structural dome		upward bulge in layered rocks	• roughly a bull's eye pattern • dip away from center • oldest in center • youngest farthest from center
structural basin		downward bulge in layered rocks	• roughly a bull's eye pattern • dip toward center • youngest in center • oldest farthest from center

In these lab activities, we focus on the responses of one material to a variety of stress. Then we examine various folds and faults in more detail.

PART 1: EXPLORING STRESS AND STRAIN

Working with a piece of silly putty, subject it to various stresses—large or small force, force applied rapidly or gradually—and combinations of those stresses. How does it strain in response to each of these? Describe the behavior of this material in the table below. What structures could result from these conditions?

Stress magnitude / Resulting strain / Stress rate	***High stress***	***Low stress***
Stress applied quickly		
Stress applied slowly		

PART 2: ORIGAMI

You are provided with six flat diagrams that can be folded into 3-D blocks. It isn't necessary to do the folding to complete the exercise, but you may find it helpful. To fold the blocks, remove the pages from your lab manual, cut them out, and fold to form a block. Each diagram has a series of geologic units that are drawn in on some but not all of the faces. Your job is to draw the contacts of the units on the remaining faces and complete any other instructions or questions associated with each block.

Remember that along the edges of the 3-D box - where the sides meet the top or where the sides meet each other - the geology must match. That is, the geology along a cross-section must match the geology of the map where the two planes intersect. You can use this to accurately transfer information from the map to the cross sections or vice versa.

1. BLOCK 1
   a. Complete the map portion of this block diagram. Draw in all necessary contacts and label each unit.
   b. Name the structure that occurs in the diagram.

      Draw the proper symbol for that structure on the map portion of the diagram.
   c. On the map, add one representative strike and dip symbol for each limb of the fold.
   d. Which unit is the youngest? Which is the oldest?

2. BLOCK 2
   a. Complete the two remaining sides of this block diagram. (Some information has been provided for you.) Draw in all contacts and label all units.
   b. Put accurate strike and dip symbols on each unit on the map.
   c. What structure(s) occurs in this diagram?

      Is/are the structure(s) plunging or not plunging?

      Draw the appropriate symbol(s) for this/these structure(s).
   d. Which unit is the youngest? Which is the oldest?

3. BLOCK 3
   a. Complete all four cross-sections for this diagram. (One cross-section has been started for you.)
   b. Put accurate strike and dip symbols on each unit on the map.
   c. What structure(s) occurs in this diagram?

      Is/are the structure(s) plunging or not plunging?

      Draw the appropriate symbol(s) for this/these structure(s).
   d. Add arrows to the map or cross-sections of the block diagram to indicate the nature of offset on the fault.
   e. Which unit is the youngest? Which is the oldest

4. BLOCK 4
   a. Complete the remaining sides of this block diagram. (Some information has been provided for you.) Draw in all contacts and label all units.
   b. Put accurate strike and dip symbols on each unit on the map.
   c. What structure(s) occurs in this diagram?

      Is/are the structure(s) plunging or not plunging?

      Draw the appropriate symbol(s) for this/these structure(s).
   d. Which unit is the youngest? Which is the oldest?

5. BLOCK 5
   a. Complete the remaining sides of this block diagram. (Some information has been provided for you.) Draw in all contacts and label all units.
   b. Put accurate strike and dip symbols on each unit on the map.
   c. What structure(s) occurs in this diagram?

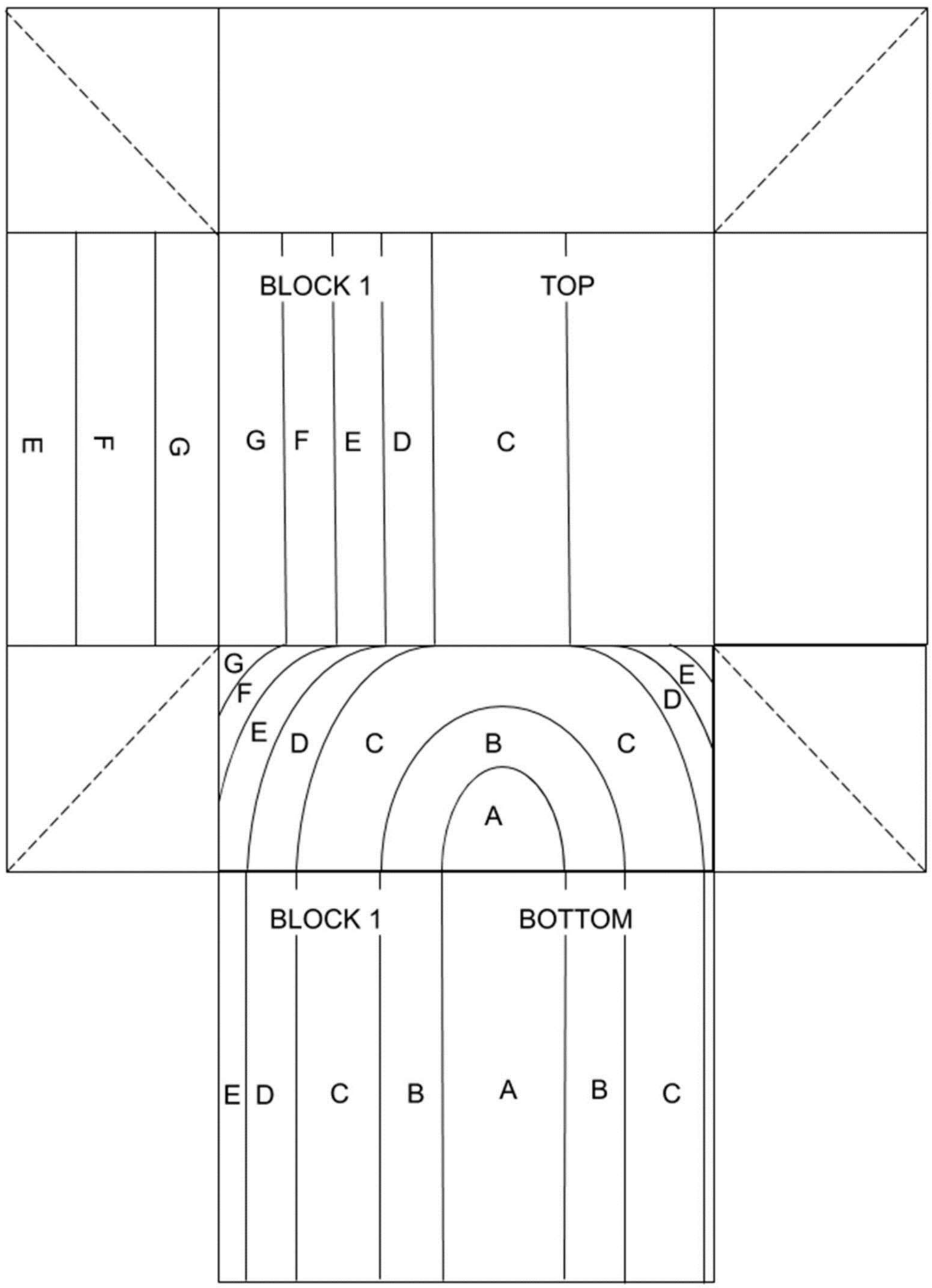
      Is/are the structure(s) plunging or not plunging?

      Draw the appropriate symbol(s) for this/these structure(s).
   d. Which unit is the youngest? Which is the oldest?

6. BLOCK 6
   a. Complete the remaining sides of this block diagram. (Some information has been provided for you.) Draw in all contacts and label all units.
   b. Put accurate strike and dip symbols on each unit on the map.
   c. What structure(s) occurs in this diagram?

      Is/are the structure(s) plunging or not plunging?

      Draw the appropriate symbol(s) for this/these structure(s).
   d. Which unit is the youngest? Which is the oldest?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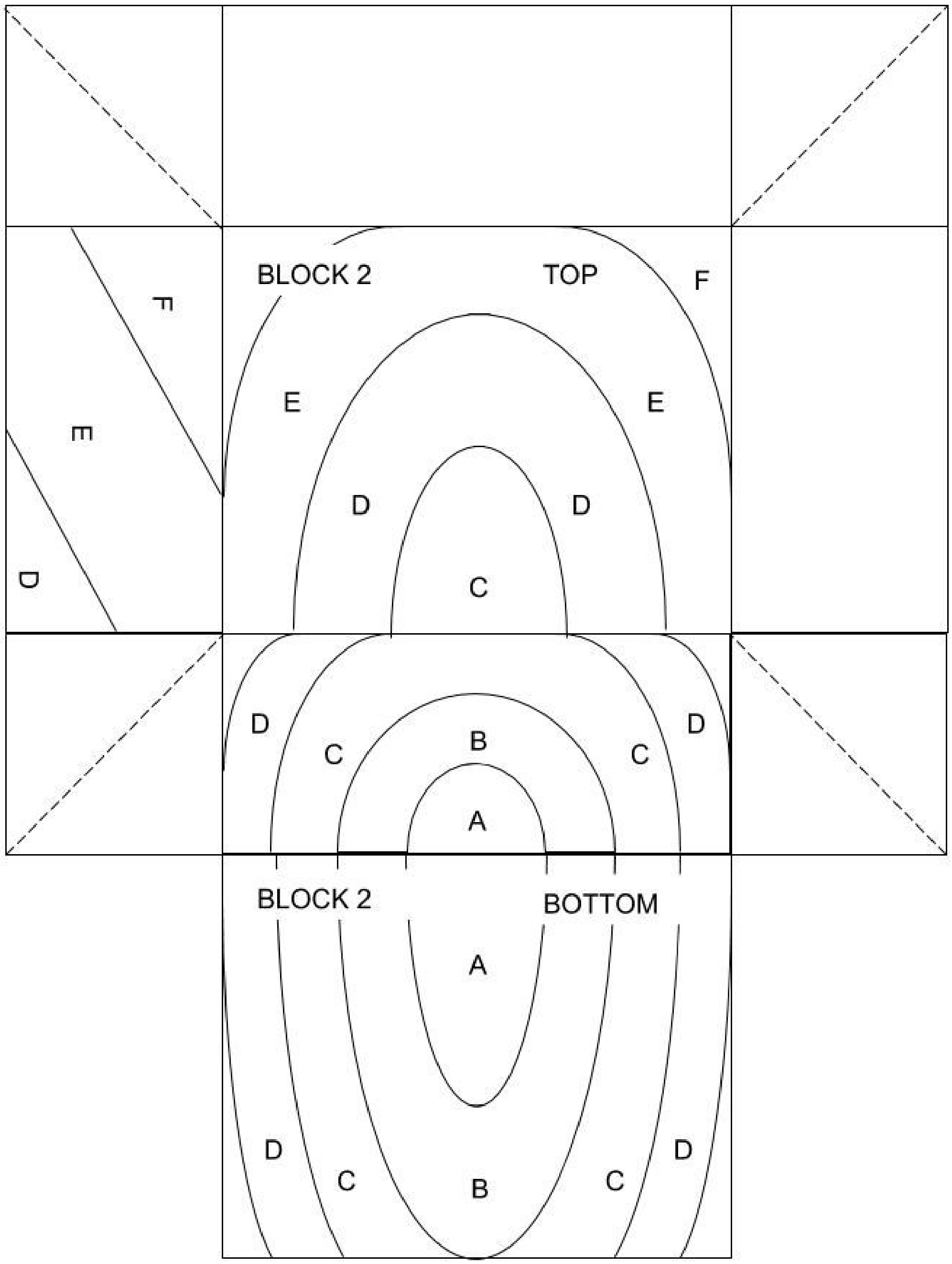
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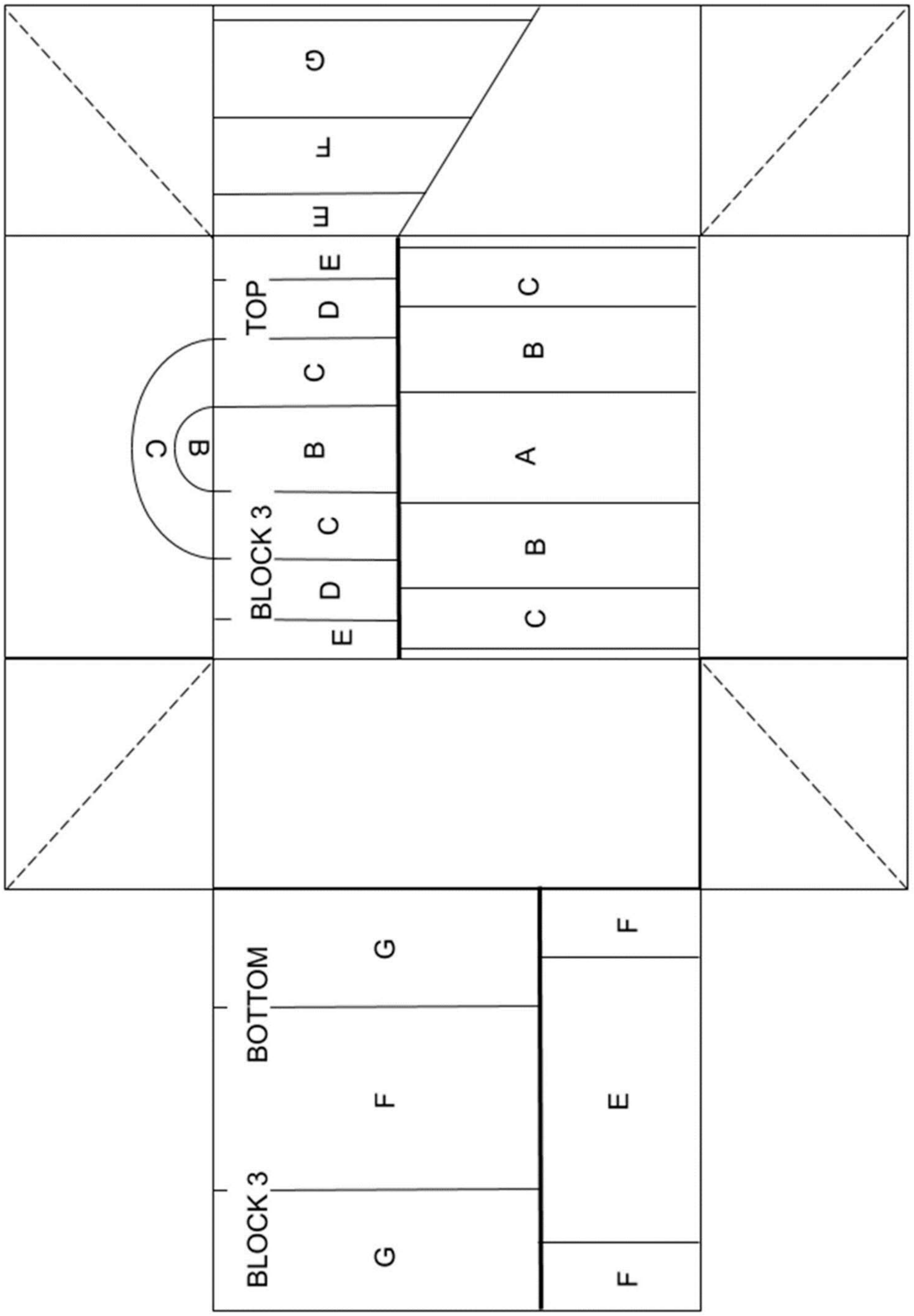
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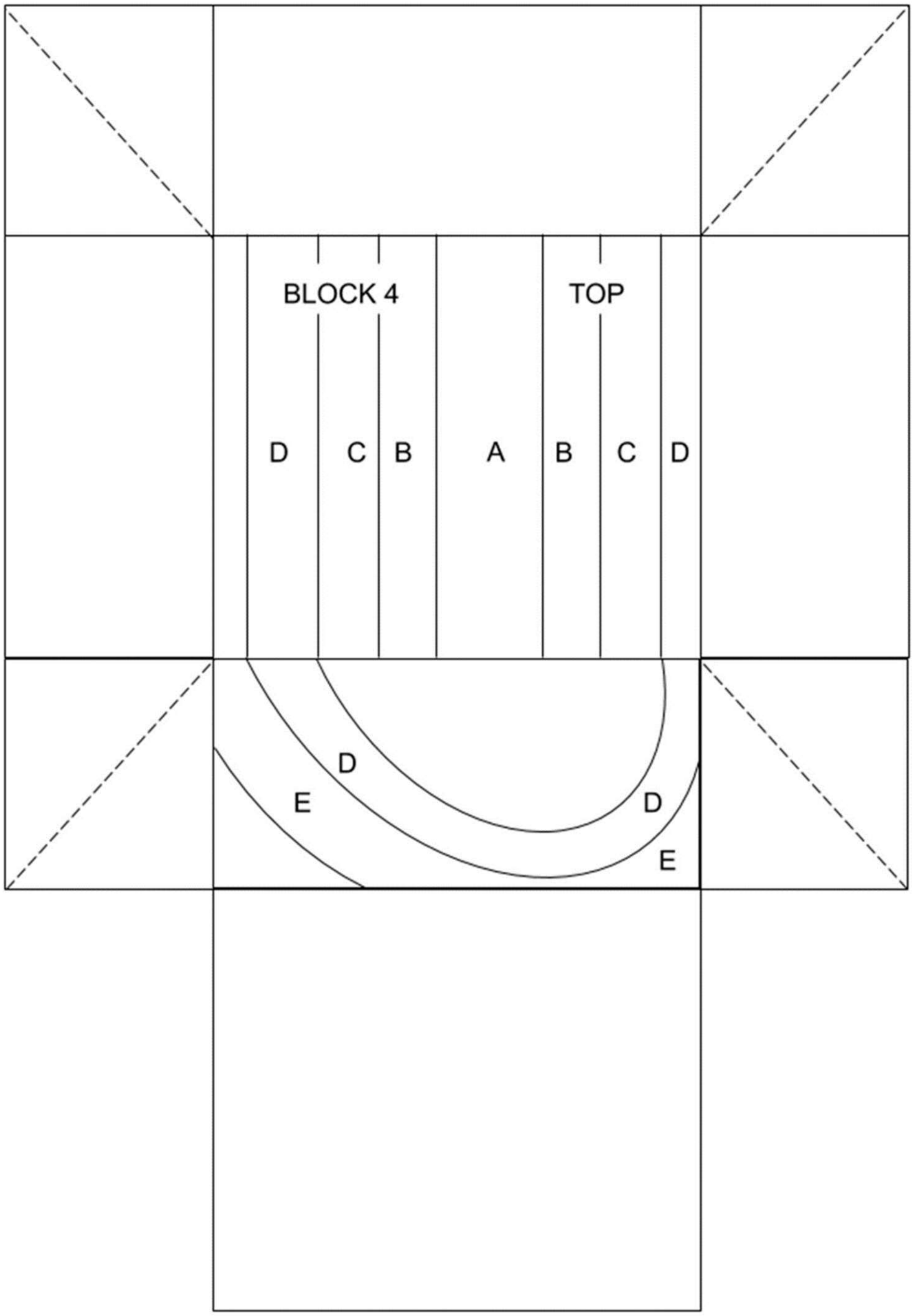
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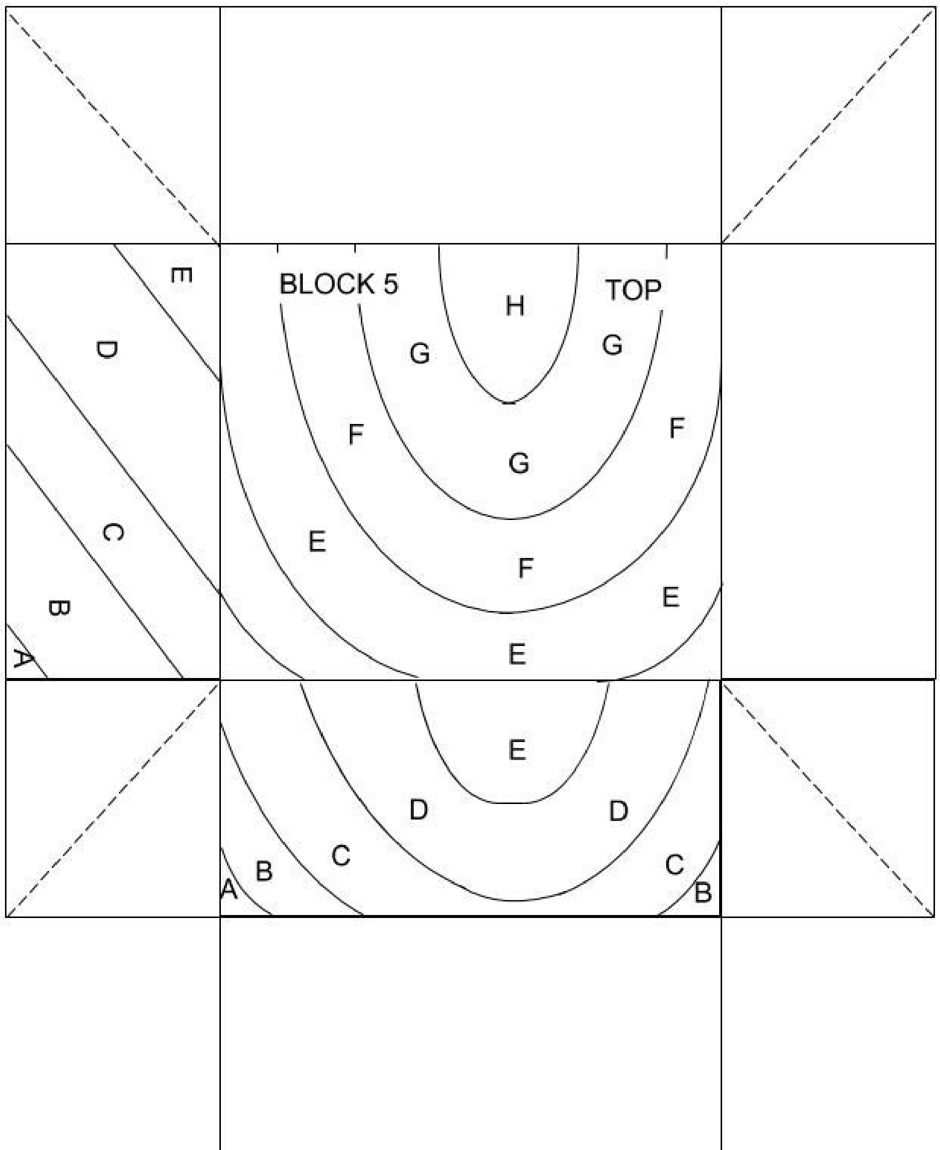
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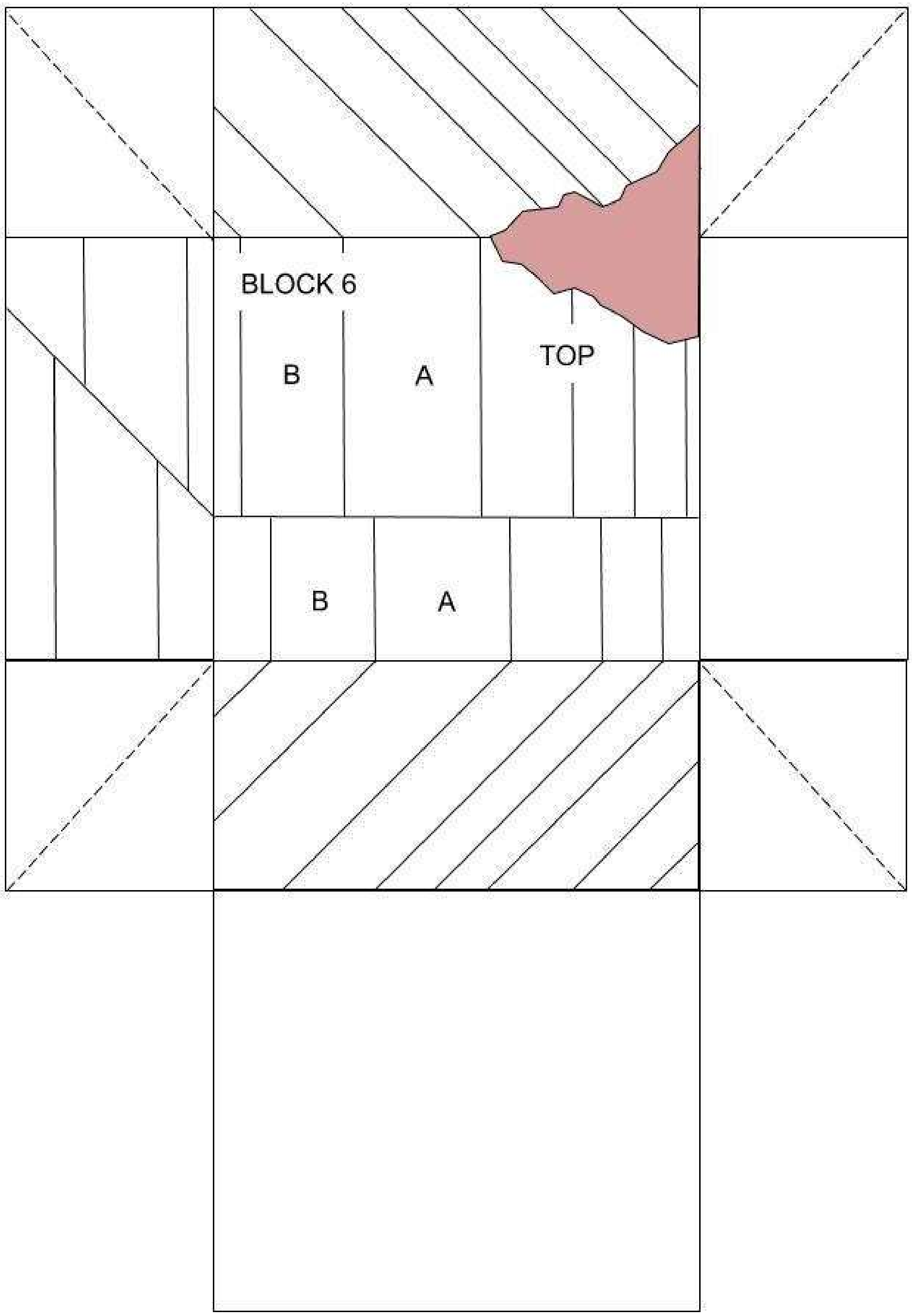
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Lab 10—Geologic maps and cross sections

In much the same way that topographic maps project the three-dimensional shape of earth's surface onto a two-dimensional map, geologic maps project information about bedrock geology onto a two-dimensional surface. In general, geologic maps show you what bedrock would be evident at a given location on a map once the soil and vegetation are stripped away. In addition to labeling the type of rock, geologic maps will have the age of rocks, names of rock formations, and structural information such as faults, strikes and dips, and geologic cross sections.

Geologic maps are a fundamental tool for every geologist. To interpret a geologic map, you must have a working knowledge of map reading, principles of stratigraphy, the geologic time scale, rock types, and structural geology. Essentially, the lab you are doing today is a synthesis of all we have covered thus far in this semester. Once one can read a geologic map, they can be given a map of a location they have never visited, or even heard of, and tell a reasonable story about the geologic history of that place.

For today's lab you will use geologic and elevation maps of Kentucky to answer a set of questions guiding you through the interpretation of Kentucky's geologic history. You will find 8 ½" by 11" copies of these maps in your lab manual as well as a few larger, more detailed geologic maps of Kentucky in the classroom that need to be shared.

Follow the same lab report structure used for all other labs in this course. **For the discussion section of your lab report this week**, please summarize in paragraph form or using a bullet-point list, whichever is more comfortable for you, the geologic history and setting of Kentucky.

PART 1: Broader context

Figure 10.1. Regional tectonic map of the midwestern United States (2019)

1. How many tectonic regions does Kentucky span? What are their names?

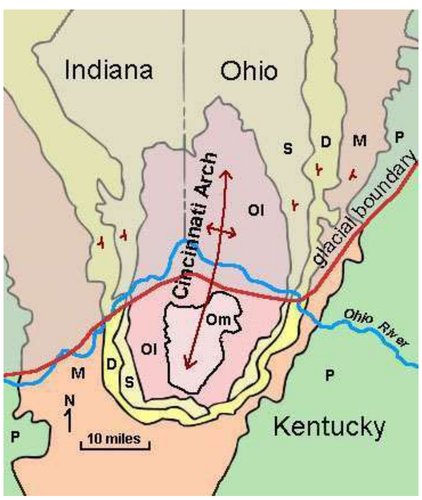

Figure 10.2. Generalized geologic map of Cincinnati Arch (Stoffer, 2015)

2. Compare the age of the rocks in the center of the Cincinnati Arch with the ages of the rocks further away. Considering this and the structure symbols in figure 10.2, what structural feature is the Cincinnati Arch?

PART 2: For questions 3–15, refer to the geologic and topographic maps of Kentucky (Fig. 10.3 and Fig. 10.4, respectively).

3. How does the map pattern indicate that the rock layers underlying Kentucky are flat lying to gently dipping?

4. What age of rocks are found around Highland Heights, in fact, all along the Ohio River in northern Kentucky and southwestern Ohio?

5. What fossils are commonly found in this unit?

6. Where is the highest topographic point in Kentucky? Explain its occurrence using bedrock geology.

7. What are the oldest rocks beneath the state of Kentucky?

8. What age are they?

9. Where do they crop out at the surface?

10. As you drive from Highland Heights, KY, to Cairo, IL, the rocks get progressively [***older*** or ***younger***—pick one] in age.

11. How can you explain this age progression?

12. Considering what you have learned so far, what geologic structure(s) do you see expressed in the Bedrock Geologic Map of Kentucky? Draw the corresponding map symbol(s) on your 8 ½” x 11” copy of this map.

13. What patterns do you see that lead you to that conclusion?

14. Draw strike and dip symbols on your 8 ½” x 11” map.

15. Using Steno’s principles of stratigraphy, draw an estimated geologic cross-section for the 8 ½” x 11” Bedrock Geologic Map of Kentucky:

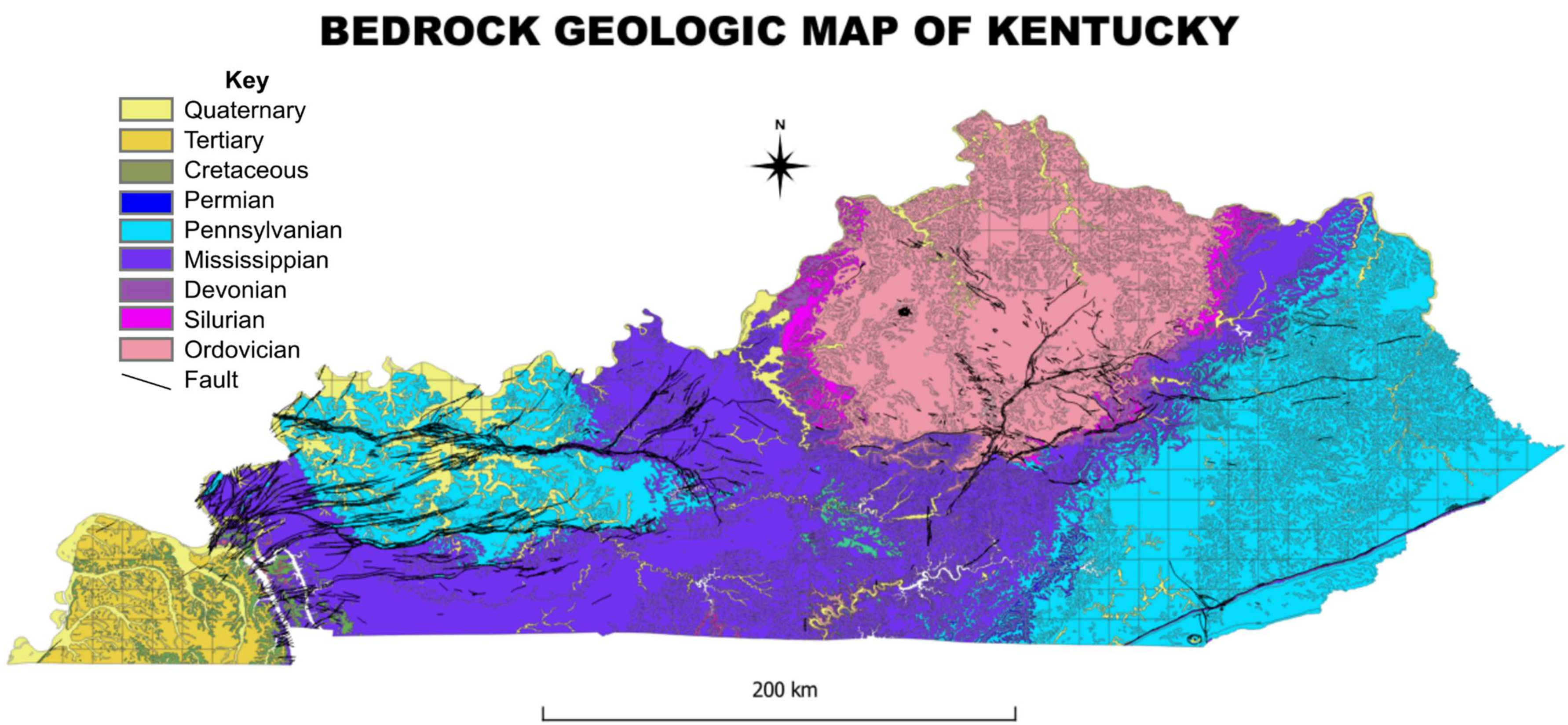

Figure 10.3. Geologic Map of the state of Kentucky, USA. Cartography in QGIS by author. Data from United Stated Geologic Survey (https://mrdata.usgs.gov/geology/state/; last access 1 July 2021)

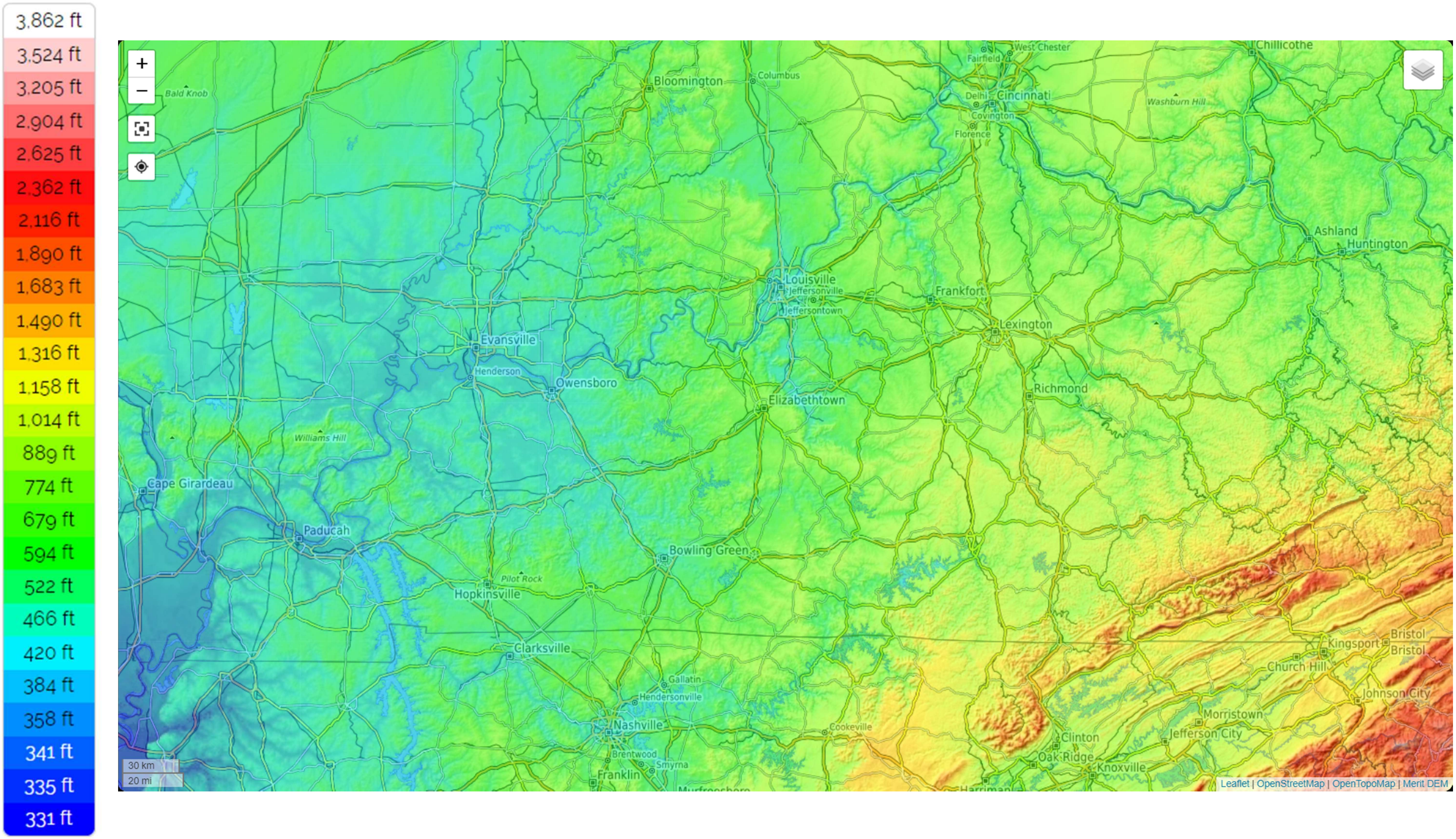

Figure 10.4. Topographic Map of Kentucky. For the full, interactive version, go to [*https://en-us.topographic-map.com/maps/ag/Kentucky/*](https://en-us.topographic-map.com/maps/ag/Kentucky/)*.*

STRATIGRAPHY

The Geologic Map of Kentucky shows the distribution of sedimentary strata totaling as much as 15,000 ft in thickness and ranging in age from Middle Ordovician to Holocene, with minor amounts of Permian intrusive rocks. The seven columnar sections on the map portray the subdivision of the sedimentary sequence into stratigraphic units and graphically indicate the general lithic character of these units. In addition, eight diagrams on the map illustrate complex stratigraphic relationships. A correlation chart of the stratigraphic units used on the map has been published separately (McDowell, 1981).

This section presents descriptive summaries of the stratigraphic units in Kentucky, grouped by system; they were prepared (in most cases) by geologists who have been closely involved in analysis and mapping of the units during the cooperative mapping project. These summaries provide details of lithology, occurrence, and correlation that could not be included on the State geologic map; many of the summaries also discuss origins of the nomenclature, type localities, depositional environments, and regional aspects of the depositional basins and give references to more extensive or detailed published stratigraphic analyses.

The descriptions of the rocks in each subsection are given by map unit as used on the State geologic map. This necessitates combination or division of some formal stratigraphic units, as well as multiple descriptions of a few formations that are shown in different map units in different regions of the State.

The few map units that include systemic boundaries are described primarily under the system to which most of the unit is referred; for example, the New Albany Shale is discussed in the summary of the Devonian.

Continuing studies have resulted in some revisions of the nomenclature used on the geologic map, specifically in the Silurian and Mississippian of eastern Kentucky and the Pennsylvanian of western Kentucky. The descriptions are keyed to the stratigraphic units used on the map, but the revised nomenclature is also presented for comparison and future reference.

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ORDOVICIAN SYSTEM

By Earle R. Cressman and Warren L. Peterson

Approximately 1,400 ft of Ordovician rocks are exposed in Kentucky. The Ordovician is the oldest system that crops out in the State, and the base is not exposed. In most areas the Ordovician is overlain disconformably to paraconformably by the Silurian, but in the southern Bluegrass region from Lebanon in Marion County to south of Stanford in Lincoln County (sheet 2) rocks of Devonian age rest directly on the Ordovician as a result of post-Middle Silurian to pre-Middle Devonian arching and erosion along an ancestral Cincinnati arch.

By far the largest area of exposure of the Ordovician rocks is in central and north-central Kentucky along the crest and flanks of the Cincinnati arch (figs. 1, 2). The area of exposure, approximately 7,600 mi^2, is coincident with the Bluegrass region (see physiographic diagram on sheet 1 of the geologic map). The Inner Bluegrass is underlain by Middle Ordovician rocks (fig. 1), and the Outer Bluegrass by Upper Ordovician rocks (fig. 2). Upper Ordovician rocks also crop out in two smaller areas in the south-central part of the State. These are along the Cumberland River and its tributaries from Wolf Creek Dam downstream to the Tennessee border and in southern Allen County along several tributaries to the Barren River.

The Middle Ordovician consists mostly of limestone. The lower part, the High Bridge Group, is mostly of sparingly fossiliferous micrite and minor dolomite that was deposited in shallow lagoons and on tidal flats; the upper part, the Lexington Limestone, is mostly very fossiliferous limestone and fossil-fragmental calcarenite. The Upper Ordovician section consists of interbedded fossiliferous limestone or dolomite and shale; shale dominates some parts of the section, and limestone or dolomite other parts. Both the Lexington Limestone and the Upper Ordovician rocks were deposited in tropical latitudes in shallow marine water on a shelf that sloped gently northward.

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SILURIAN SYSTEM

By Warren L. Peterson

The Silurian rocks crop out in Kentucky in narrow arcuate belts on the east and west flanks of the Cincinnati arch and in small isolated areas mostly in south-central Kentucky (fig. 3). The Silurian rocks are of marine origin and are composed of dolomite and shale and minor amounts of limestone and chert, with a total thickness ranging from 0 to 300 ft. The basal contact is a minor erosional unconformity in much of the outcrop area; elsewhere it is probably conformable or paraconformable. The upper contact is a regional erosional unconformity, and on the crest of the Cincinnati arch the entire Silurian section has been removed. The large variation in thickness is caused by erosion along this unconformity. The original thickness of the Silurian strata is not known, as the upper part has been everywhere removed.

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DEVONIAN SYSTEM

By Roy C. Kepferle

Exposed Devonian rocks in Kentucky (fig. 5) range in thickness from 4 ft in south-central Kentucky (Cattermole, 1963), where they are cut out by a limestone-filled channel in the Mississippian Fort Payne Formation, to more than 1,000 ft along the west flank of Pine Mountain in eastern Kentucky (Alvord, 1971; Wolcott, 1974). In general, the sequence thickens away from the crest of the Cincinnati arch. Westward, in the Illinois basin, the subsurface Devonian section thickens to 1,800 ft; the upper 470 ft is shale, and the remainder is limestone and dolomite (data extrapolated from Collinson and Atherton, 1975, p. 105; Schwalb and Norris, 1980a, b, c). Eastward, in the Kentucky part of the Appalachian basin, the subsurface thickness approaches 2,000 ft (de Witt and others, 1975, sheet 1), of which more than 1,800 ft in the upper part of the sequence is shale (Fulton, 1979; Dillman and Ettensohn, 1980). Carbonate rocks of Middle Devonian age make up the basal part of the Devonian sequence in Kentucky outcrops. These include the Jeffersonville Limestone, the Sellersburg Limestone (the North Vernon Limestone of the Indiana Geological Survey), and the Boyle Limestone or Dolomite. Organic-rich black to brownish-black shale and lesser amounts of grayish-green shale are everywhere present in the Upper Devonian sequence in Kentucky. A thin bed or lamina of impure, phosphatic quartzose sandstone is common on the widespread basal unconformity; other sandstone beds, or "bone beds," lie locally within or at the top of the carbonate rocks, as well as within the basal few feet of the overlying shale. These bone beds are attributed by Conkin and Conkin (1969) to widespread erosional unconformities preceding and during Devonian deposition.

The basal unconformity truncates rocks ranging in age from Late Ordovician on the crest of the Cincinnati arch to Middle and Late Silurian on the flanks of the arch. In most exposures, this unconformity appears planar, as in the vicinity of Jefferson County, where it can be followed without interruption for nearly a mile along the north side of Interstate Highways I-71 and I-264. Where the unconformity truncates rocks of contrasting hardness, as in south-central Kentucky (Simmons, 1967; Kepferle, 1973), the Devonian carbonates and shales are thick over easily eroded Silurian shale but thin over nearby Silurian-dolomite capped cuestas or monadnocks. The limestone and dolomite at the base of the Devonian sequence are also thicker in structurally negative areas such as the Illinois basin and the southern part of the Appalachian basin, and several areas along the Cincinnati arch where syndepositional tectonism appears to have exerted minor influence. The erosion that preceded the Middle Devonian accumulation of carbonate rocks took place during an interval of mild tectonic warping along structures such as the incipient Cincinnati arch and the tighter folds that parallel or are normal to the present strike of the Appalachian Valley and Ridge province and the Pine Mountain thrust fault.

The Devonian rocks of Kentucky accumulated in a gradually deepening epeiric sea (Kepferle, 1977, p. 41; Jordan, 1980; Ettensohn and Barron, 1981, p. 59, 69). This is inferred from the upward facies change from carbonate at the base to clay-rich shale at the top and from the lack of evidence of subaerial exposure within the sequence.

For purposes of discussion, the Devonian rocks are grouped in five general areas of outcrop (see fig. 5): (1) the west flank of the Cincinnati arch, where the rocks dip gently westward into the Illinois basin along a line extending southward from the

Ohio River in Jefferson and Oldham Counties to the sharp eastward bend in the outcrop in Nelson and Larue Counties; (2) the faulted and warped Cumberland Saddle area of outcrop extending eastward and northeastward through Madison and Estill Counties and southward in discontinuous exposures to the Tennessee border; (3) the northward-extending outcrop on the east flank of the Cincinnati arch where the bedrock dips gently eastward into the Appalachian basin; (4) the discontinuous exposures in the sole of the Pine Mountain thrust fault on the west flank of Pine Mountain; and (5) minor exposures beneath the more recent sediments in the faulted Mississippian Embayment area of the Jackson Purchase region of Marshall and Lyon Counties. The carbonates are thickest in the northern part of area 1 and in area 2. The shale is thickest in the northern parts of areas 3 and 4. Thickness, composition, and paleocurrent data suggest that the source of terrigenous elastics lay to the east during much of the Devonian period (Kepferle, Lundegard, and others, 1978; Potter and others, 1979).

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MISSISSIPPIAN SYSTEM

By George J. Grabowski, Jr.

The Mississippian System in Kentucky is represented by mostly marine sedimentary rocks which originally extended across the entire State. These rocks record a widespread shallowing of the seas during Mississippian time, with basinal and prodeltaic shales and siltstones succeeded by shelf limestones and dolomites and coastal sandstones and shales. The Mississippian rocks are widely distributed, cropping out mainly in central and western Kentucky and underlying the Illinois and Appalachian basins (fig. 6). They are economically important in some areas and locally present environmental hazards. Additional information on the geology of the Mississippian System in Kentucky is given in three recent summary papers: Pryor and Sable (1974), Sable (1979), and Rice, Sable, and others (1979). Nomenclature of the upper part of the Mississippian section along the Pottsville Escarpment of eastern Kentucky, including essentially post-Borden strata, has recently been revised by Ettensohn and others (1984). The description of map units below is arranged generally as follows: Lower Mississippian, Upper Mississippian of western Kentucky, Upper Mississippian of eastern Kentucky, and Mississippian of Pine Mountain.

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PENNSYLVANIAN SYSTEM

By Charles L. Rice

Pennsylvanian strata crop out in two broad areas of Kentucky which together represent more than one third of the area of the State (fig. 8). These deposits are in parts of two major sedimentary basins: the Appalachian basin, which contains the eastern Kentucky coal field underlying the Cumberland Plateau, and the Eastern Interior

(Illinois) basin, which contains the western Kentucky coal field (see physiographic diagram on sheet 1 of the geologic map). Most workers, including some of the earliest to investigate the system such as Shaler (1887) and Burroughs (1923), believe that Pennsylvanian strata once formed a continuous deposit across central Kentucky and the Cincinnati arch. Erosion since the close of the Paleozoic has removed many hundreds, perhaps thousands, of feet of Pennsylvanian and older strata from the structurally higher areas such as the Cincinnati arch, which separates the two basins, and has resulted in the present outcrop pattern. The distance between the two basins is much less than is apparent at first glance: close inspection of the geologic map shows that the easternmost salient of the western Kentucky coal field, on hilltops on the county line between Taylor and Larue Counties (Moore, 1976), is only about 45 mi from outliers of the eastern Kentucky coal field, on hilltops along the county line between Casey and Pulaski Counties (Lewis and Taylor, 1974).

The Pennsylvanian rocks of the two basins are lithologically similar and consist largely of sandstone, siltstone, and shale. Coal beds and thin marine shale and limestone units are widespread and occur in most parts of the stratigraphic section. These deposits indicate that in Pennsylvanian time Kentucky was near sea level, alternately covered by lakes, extensive swamps, shallow bays, and estuaries. Thus piedmont, alluvial, and coastal-plain environments extended across the State at times during the Pennsylvanian, resulting in the deposition of the strata of the two great coal fields.

The western Kentucky coal field contains, at the top of the section, a few hundred feet or more of strata of Permian age (Kehn and others, 1982). These beds are described in the section on the Permian System.

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PERMIAN SYSTEM

By Robert C. McDowell

Permian rocks occur in Kentucky as minor igneous intrusives and as a few hundred feet of sediments at the top of the Paleozoic section in the western coal basin. These sediments, shown on the columnar section for western Kentucky, sheet 1 of the geologic map, as the uppermost part of the Sturgis Formation (PPS), have subsequently been removed from the Sturgis and renamed the Mauzy Formation (Kehn and others, 1982).

The igneous intrusives are of two types: lamprophyre and peridotite dikes and sills in Caldwell, Crittenden, and Livingston Counties of the western Kentucky fluorspar district and three small peridotite intrusions in Elliott County, northeastern Kentucky (fig. 11). Both types are considered Early Permian in age on the basis of K-Ar and Rb-Sr dating of biotite (Zartman and others, 1967). They constitute the only outcropping igneous rocks in Kentucky.

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CRETACEOUS AND TERTIARY SYSTEMS

By Wilds W. Olive and Robert C. McDowell

Cretaceous and Tertiary strata in Kentucky are restricted mostly to the Jackson Purchase region of far western Kentucky (see fig. 18 or physiographic diagram on the geologic map). Pliocene and possibly upper Miocene sediments are also found with Pleistocene sediments in continental deposits that occur in the Jackson Purchase and elsewhere in western Kentucky; these younger units are discussed in the section on the Quaternary System. This section concerns the post-Paleozoic strata (see columnar section for western Kentucky on sheet I of the geologic map) that are distributed throughout the Jackson Purchase beneath a veneer of Miocene(?) to Holocene continental deposits, loess, and alluvium (fig. 12).

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QUATERNARY SYSTEM

By Robert C. McDowell and Wayne L. Newell

Quaternary deposits occur locally (along with minor amounts of Miocene(?) or Pliocene sediments) as a relatively thin surficial veneer in all parts of Kentucky and as thick and extensive sequences in northern and western Kentucky. The mappable deposits are of three main types: high-level fluvial deposits, underlying Pliocene and Pleistocene terraces; glacial deposits and loess, of Pleistocene age; and alluvium, underlying Pleistocene and Holocene terraces and flood plains. The Quaternary sediments consist of unconsolidated gravel, sand, silt, and clay and locally contain sparse to abundant organic matter, including redeposited coal. During the cooperative mapping program, geology of the Paleozoic bedrock was emphasized; as a result portrayal of surficial deposits varied with the locality and the mapper. Consequently, compilation of Quaternary deposits for the Geologic Map of Kentucky required considerable generalization. Five map units are shown: continental deposits, continental deposits with loess, high-level fluvial deposits (shown as an overprint), glacial deposits, and alluvium. Continental deposits (with or without loess) have been mapped only in far western Kentucky and are shown only on sheet 1 of the geologic map; high-level fluvial deposits are shown on sheets I and 2, and glacial deposits and alluvium are shown on all three sheets.

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NOTES

Lab 11—Geophysical Field Methods

What is Geophysics?

Geophysics is the study of the physical processes and physical properties of the Earth and its surrounding space environment, and the use of quantitative methods for their analysis. Data that is gathered relies upon the interactions of Earth's materials with physical fields:

- Density, electrical resistivity, electrical fields and radioactivity of rocks;
- Velocity of sound waves transmitted through the ground;
- Changes in gravity and magnetic fields of the Earth; or
- Reflection of radio signals from rocks near the Earth's surface.

Geophysicists use one or more of these measurements to find oil, natural gas, potash, coal, iron, copper and many other minerals. In addition, the properties are used to identify environmental hazards and evaluate areas for dams or building construction sites.

Definitions given by the Environmental and Engineering Geophysical Society (n.d.) are as follows:

1. Geophysics is: The subsurface site characterization of the geology, geological structure, groundwater, contamination, and human artifacts beneath the Earth's surface, based on the lateral and vertical mapping of physical property variations that are remotely sensed using non-invasive technologies. Many of these technologies are traditionally used for exploration of economic materials such as groundwater, metals, and hydrocarbons.
2. Geophysics is: The non-invasive investigation of subsurface conditions in the Earth through measuring, analyzing and interpreting physical fields at the surface. Some studies are used to determine what is directly below the surface (the upper meter or so); other investigations extend to depths of 10's of meters or more.

Both of these definitions have a common component, namely that geophysics represents a class of subsurface investigations that are non-invasive (i.e. that do not require excavation or direct access to the sub-surface). The exceptions are borehole geophysical methods that expand the use of holes already drilled to access the subsurface on a very localized basis.

In addition, Definition 1. focuses on the key targets of interest (i.e. geology, geological structure, etc.) - a key consideration in understanding the realm of Environmental and Engineering Geophysics.

Definition 2. underscores the near surface aspect (i.e. in contrast to other geophysical applications, such as petroleum or mineral exploration, this type of problem solving deals with shallow depths that are most significant in terms of the lives, work and activities of the earth's human population.)

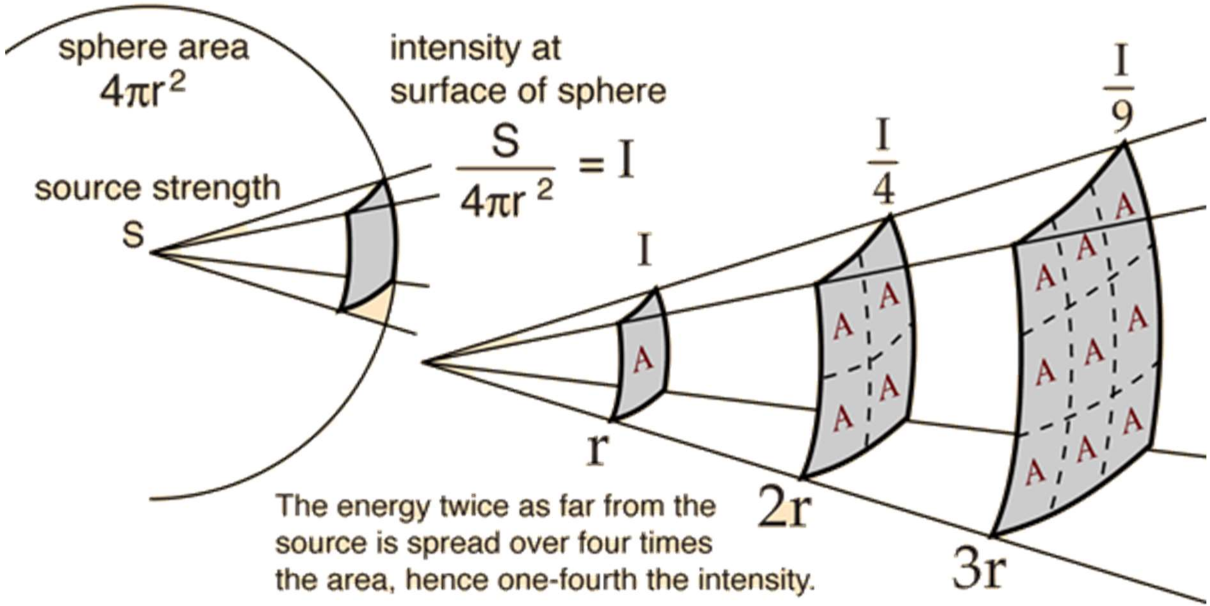


Figure 11.1. Illustration of the general behavior of fields obeying an inverse-square law (from Nave, n.d.).

Geophysical studies are premised upon the interactions of Earth's materials with physical fields. These fields obey the inverse-square law of physics (Fig. 11.1). "Any point source which spreads its influence equally in all directions without a limit to its range will obey the inverse square law. This comes from strictly geometrical considerations. The intensity of the influence at any given radius r is the source strength divided by the area of the sphere. Being strictly geometric in its origin, the inverse square law applies to diverse phenomena. Point sources of gravitational force, electric field, light, sound or radiation obey the inverse square law" (Nave, n.d.).

Examples of five different fields used in geophysics than can be described using inverse-square laws include Newton's law of universal gravitation,

$$F_g = \frac{Gm_1m_2}{r^2},$$

where F_g is the gravitational force, G is the gravitational constant, m_1 and m_2 are the masses of two objects, and r is the distance between them; sound, applicable to geophysics in the form of seismic waves, $I = \frac{W}{4\pi r^2}$, where W is the power of the sound source and I is the intensity in decibels at a distance of r from that source; Coulomb's law for the electrical force between two charged particles (with charges of q_1 and q_2), $F_e = \frac{kq_1q_2}{r^2}$, where k is a constant; radar, $P_r = \frac{P_tG_tA_r\sigma F^4}{(4\pi)^2r_t^2r_r^2}$, since radar calculations need to account for the emitted waves and the received waves, r^2 shows up twice in the denominator; and the one that applies directly to this week's lab, magnetism, $F_m = \frac{\mu p_1p_2}{r^2}$, where μ is a constant, and p_1 and p_2 are the strength of two independent magnetic poles.

Near-surface geophysical surveys are conducted, as their name implies, to characterize the nature of the subsurface just below the surface. These include ground-penetrating radar surveys, shallow seismic surveys, electrical resistivity surveys, and the kind you are going to do in the following activity: magnetometry surveys.

Geophysics Activity—Magnetometry at home: a hands-on survey with your smartphone (Bank, 2021)

Geophysical surveys, including magnetometry, take advantage of contrasts in physical properties between targets in the subsurface and the material surrounding them. These property contrasts allow us to measure variations in some quantity at or above the surface and then interpret what may be present in the subsurface. My team has used magnetometry for example to locate buried firearms[1] or to determine depth to bedrock[2] or for a historical archaeology project[3].

What are other (maybe more common) targets for magnetometry? Do an internet search, or check a geophysics textbook, to find an interesting discovery that was made using magnetometry and share it on the discussion board.

This exercise will allow you to think through the process of a magnetic survey; however, it was designed during the COVID-19 pandemic so assumes minimal ability to move about. To accommodate your particular situation (are you able or allowed to leave your home? can you run a survey in the yard or the driveway if you live in a house? can you access a park?) you are asked to use a known magnetic target (a fridge magnet, a car, a fence, a lamp post) and measure its magnetic effect. The main goal of this exercise is to have you perform and document a survey. You will be completing a worksheet and can look at an example we created from a tabletop survey (Toronto is under lockdown as I am preparing this). In a follow-up exercise you are given magnetic data that was collected in a field survey and will be analysing that by comparing it to a model you create. If you are lucky and have access to a backyard with a known buried target (for example a near-surface buried metal pipe) you can follow this exercise by running a survey there.

Learning outcomes:

This exercise will allow you to

1. select a target and design a magnetic survey,
2. collect field data (with field being very broadly defined) using a free app,
3. document your survey,
4. graph the data you obtained,
5. complete a simple quantitative analysis, and
6. communicate your findings.

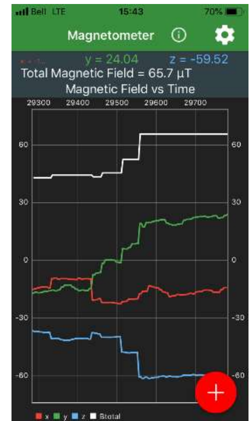
[1] Deng, E. A., K. O. Doro, and C-G Bank, 2020. Suitability of magnetometry to detect clandestine buried firearms from a controlled field site and numerical modeling, Forensic Science International, 314: 110396, https://doi.org/10.1016/j.forsciint.2020.110396

[2] Papadimitrios, K., C.-G. Bank, S. Walker, and M. Chazan, 2019. Paleotopography of a Paleolithic landscape at Bestwood 1, South Africa, from ground-penetrating radar and magnetometry, South African Journal of Science, 115(1/2), Art. #4793, 7 pg., https://doi.org/10.17159/sajs.2019/4793

[3] Wadsworth, W., C.-G. Bank, K. Patton, and D. Doroszenko, 2020. Forgotten Souls of the Dawn Settlement Project: A geophysical exploration of unmarked graves in Southwestern Ontario. Historical Archaeology, Vol 54, https://doi.org/10.1007/s41636-020-00251-7

Preparation

a) Download and install the free "physics toolbox" app, available for both Android and iOS devices (see https://www.vieyrasoftware.net/ for info and link to download). For this exercise you will just need the "Physics Toolbox Magnetometer" that you can download individually. You may be surprised how many sensors are included in your device: accelerometer, sound detector, barometer, GPS... though not all tools may be supported (e.g., my iPad cannot run the proximeter).



Magnetometer" app

b) After download, start the app. You should see a screen like the one in figure 1, the different colours mark the 3 components (x, y, z) and the total value of the magnetic field. By pressing the red button, you can record the measurements and save them as a spreadsheet (.csv) file.

c) Print a copy of this worksheet (this would resemble working with a field notebook). You may also complete it on your computer device (if you can take the computer to your survey location and have a stylus, or you can scan and insert any drawings).

And here is a question to start you off:
What feature or app on your smartphone may make use of the built-in magnetic sensor?

your answer: ____

Brief background

Magnetic surveys allow us to locate buried objects or features if they distort the Earth's magnetic field that we measure at the surface or from an aerial vehicle. These objects can be either a permanent magnet or a material that acts like a magnet because it is within a magnetic field. A magnet can both attract and repel another magnet, and the direction of force around a magnet changes. We describe a magnet as a dipole and find that the force does not point towards the magnet and that it drops off with the cube of the distance if we move in a straight line away from the dipole. This exercise allows you to confirm this relationship.

Variations in the Earth's magnetic field that are caused by a buried magnetic object are called anomalies. Because of the dipole nature of magnets most anomalies are paired (that is a positive, larger than the ambient field, and a negative anomaly arise from the same target), and anomalies for similar objects will look different depending on the latitude where we measure them. This exercise does not explore such relationships, because some of you may have to run the experiment in a very "noisy" environment (I live in a downtown apartment building), and geophysicists use more sensitive magnetometers than that in your smartphone because they need to measure very small anomalies. If you want to learn more about magnetic surveys in geophysics check out http://appliedgeophysics.berkeley.edu/magnetic/index.html (Berkeley Course in Applied Geophysics) and/or https://www.eoas.ubc.ca/ubcgif/iag/methods/meth_3/index.htm (UBC Applied Geophysics Learning Objects), the latter includes some self-test questions.

A few background questions linked to magnetic surveying in geophysics:

- What is the difference between remanent and induced magnetization? How could you distinguish between the two on a magnetic map?
- Why do we need to know the latitude of our survey to make sense of the data?
- What are key processing steps typically applied before interpreting the data?
- What are key advantages and shortcomings of magnetic surveys?
- Can magnetometry surveys be used to find buried objects on other planetary bodies?

Please share your thoughts on the discussion board. Answers to these questions are not crucial to complete this exercise. Therefore, you may think about them afterwards, especially if you are doing this exercise as part of an introductory geophysics course or if it will be followed by a field survey.

Task 1: What is the objective of your survey?
Most decisions (where to go, what equipment to take, how to set up, how large a survey) hinge on this question. In this exercise we ask you to collect magnetic data along a survey line. If you can go outside find something (a parked vehicle, a fence, . . .) and check with the magnetometer app that values are changing. Note that if you turn around on the spot, or tilt your device readings probably will change, so make sure you hold it steady while you explore for a target.
Briefly state your survey objective:

____

Task 2: General considerations
It is a good idea to consider some general questions: what are the date and time of day? Who are you with? If you are outside, what is the current weather? What are the ground conditions (did it rain, covered in snow, muddy)? Anything else noteworthy before you start?

____

____

____

Task 3: Documenting your location

Your need to communicate to another person the location (and layout) of your experiment as accurately as possible so they could exactly recreate your experiment.

3a) Handheld devices can provide your location. To find it on either iOS Maps or Google maps open the app, hold a finger on the screen at your location which "drops a pin" and scroll down (in Google maps) or tap "My Location" (in iOS) to view your latitude and longitude.
What are your GPS coordinates, and what did you use to determine them?

____

3b) Describe your exact location in point form. If you are outside look around, are there any remarkable features (a corner in a fence, a large rock, an odd-shaped tree, buildings nearby) that can help someone else find the exact spot where you are?

____

____

3c) Are there any features that may impact your survey (power lines, parked equipment, buildings, mountain, canyon, closeness to industrial operation, airport)?

____

____

3d) Draw a map sketch of your location. This should include the features you noticed in 1b. Also include a scale and the North direction. Make your sketch large enough so you can add the layout of your experiment afterwards.

You now have documented your location in three ways: by GPS coordinates, in words, and by a sketch. This may seem redundant but consider that these are complementary and all helpful for someone else to exactly recreate your survey.

Task 4: Setting up you survey
Typically, in magnetometry the deeper the buried object is, the larger an area at the surface will be affected (ie. measurements deviate from the background reading, that is called an "anomaly") and you can space your data collection points further apart. In this exercise you are asked to work very close to the object (car, fence, . . .). Your preliminary survey (Task 1) should have shown you where the magnetic field starts to change. You should start your measurements further out to have a few data points for the background value and aim for about a dozen measurement points (in easy to recreate metric steps). Note your thoughts for setting up the survey here

____

____

Add your survey setup to the sketch (Task 3d).

Task 5: Taking measurements
The magnetometer app can record the components and total value of the magnetic field with time. However, for more accurate positioning we suggest you use a tape measure (or take small steps, one foot touching the other, that can be recreated) and take screenshots at the intervals you predetermined (Task 4). It is crucial that you are able to link the screenshots to the position, unless you use a different device to take images that allow you that unique correlation between measurement and position.

5a) Please note here how you choose to make this correlation.

____

5b) How accurate are your distance and magnetic measurements? To get an estimate of the latter you may repeat some measurements (to obtain an experimental error), and/or run a timeseries at a certain location to capture the random noise in the data. If you are surveying within a building or in a busy city that noise level may be substantial. The accuracies of your measurements are . . .

for distance ____________________, estimated from _____________________.

for magnetic data __________________, estimated from _____________________.

5c) What are other settings someone else may need to reproduce your survey (ex: device is kept horizontally pointing towards target, device held at height of your hip)?

____

Task 6: Viewing and analyzing the data
Now you can transcribe your data from the screenshots into a spreadsheet or text file.

The name of your data file is ________________________

Create a plot of your data and copy it into this space (and if you can, add error bars using the info from Task 5b):

Give a brief description of your data (with a focus on the total field value). What are the highest and the lowest value? Where along your survey do they occur? What is the average (background) value? How far away do you start seeing the anomaly?

____

____

____

Task 7: Preliminary interpretation
During and at the end of a survey the geophysicist will want to ensure good quality of the data. Often this is done with a quick and simple interpretation. For this experiment you can ask:

7a) Do the variations in B_x, B_y, and B_z values make sense? If yes, why?

____

____

7b) Does the decay of the total field with distance confirm with a simple model? It should follow a r^{-3} curve (see for example http://physicsinsights.org/dipole_field_1.html). Recalculate your distance values as difference from the maximum, and your total field values as difference to the background value. Plot these recalculated values. Then try to fit a quadratic equation to those values. Show this combined graph.

Task 8: Archiving the data

Typically, there will be some protocol for how raw data has to be archived during a field campaign (e.g., in a daily directory that gets backed up). For this experiment I suggest you collate all spreadsheet data, copies of your screenshots (in this experiment these are your raw data) into one directory, and create a simple text file summarizing key information about the survey (when, who, where, how); I even suggest including a scan of your field notes (in this experiment this workbook).

Your raw data are precious. You want to have a backup of all your data and a backup of the backup to ensure that they cannot be accidentally overwritten, deleted, or lost. You or someone else may want to use your data much later when your memory is no longer fresh, or they cannot get a hold of you.

Short reflection

What in this activity or your results surprised you?

____

____

Give three examples where geophysicists may use a magnetic survey:

1.

____

2.

____

3.

____

Looking forward

Congratulations! You have run your first real geophysical survey even if you, like me, had to do it in your kitchen. Now you know the importance of planning, documenting, controlling, and archiving your data and should feel curious how to work with data collected with a real geologic/archaeologic/environmental/... question in mind. If this is indeed your next step, I encourage you to revisit the questions in the background section.

NOTES

Lab 12—Earth Systems Science

The Water Cycle as an Example

We can think of the Universe as the largest possible system (Figure 11.1). All other systems available for study are subsets of and interconnected with everything in the Universe. Each galaxy of the hundreds of billions of galaxies in our known universe is a system.

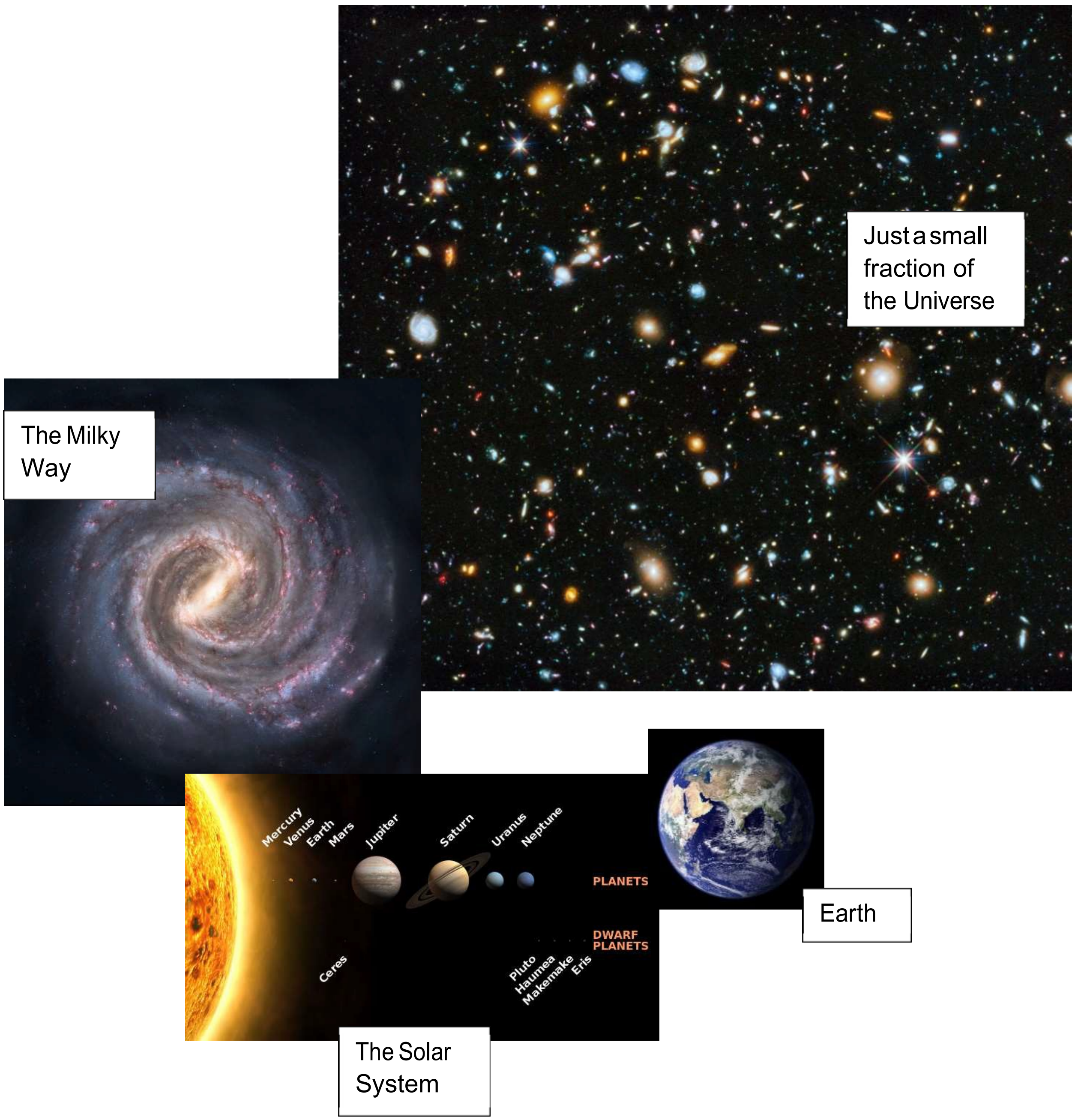


Figure 12.1. The largest system we know, The Universe, contains The Milky Way Galaxy, The Solar System, and the Earth within it.

Of the billions of star systems contained within the Milky Way Galaxy, one, The Solar System, contains our planet, Earth.

> "Earth is a complex system of interacting physical, chemical and biological processes, and provides a natural laboratory whose experiments have been running since the beginning of time.
>
> "The Earth system is often represented by interlinking and interacting 'spheres' of processes and phenomena. The atmosphere, hydrosphere, biosphere and geosphere form the simplest collection, though some would add the cryosphere as a special element dealing with polar regions and processes, and others would add the anthroposphere emphasizing human dimensions and impact on the planet. The difficulty with any representation that divides the system is the danger of continuing a deconstructed perception of the holistic Earth system - in reality no part of the Earth system can be considered in isolation from any other part." (Johnson et al., 2000)

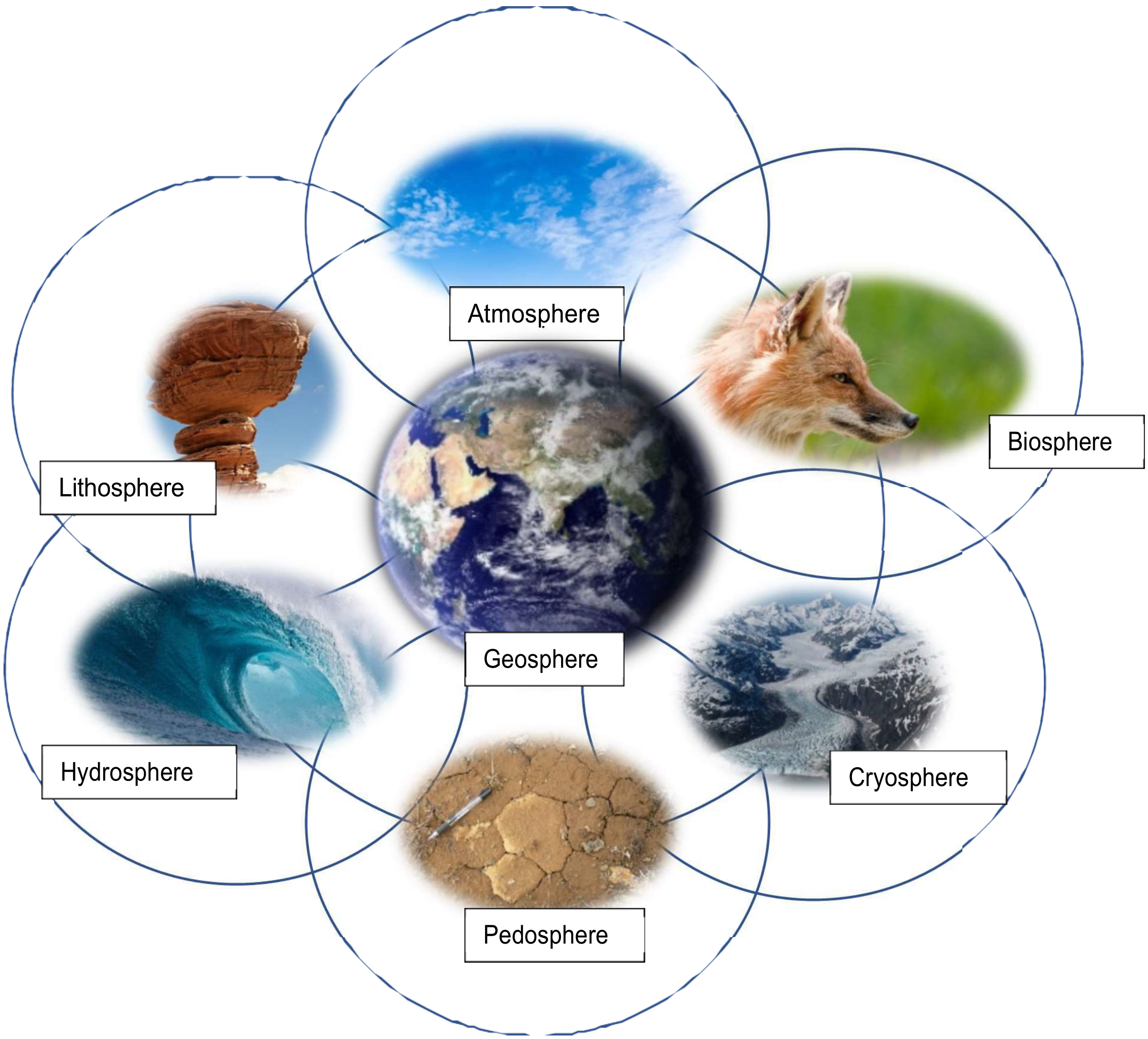


Figure 12.2. Subspheres of Earth, or the geosphere. All are interconnected systems within Earth Systems Science.

Once the geosphere is divided into many smaller systems, it becomes more manageable, but it still may feel challenging and abstract to think about any one of these spheres. One approach to tackle this scientifically is to think about some of these systems as cycles (Figure 12.3). The biosphere, for example, contains many life cycles. The lithosphere can be imagined as being illustrated by the rock cycle. Others, such as the carbon cycle, the water cycle, and the nitrogen cycle, involve processes that occur in many, if not all, of the spheres. Today we will be focusing on the water cycle.

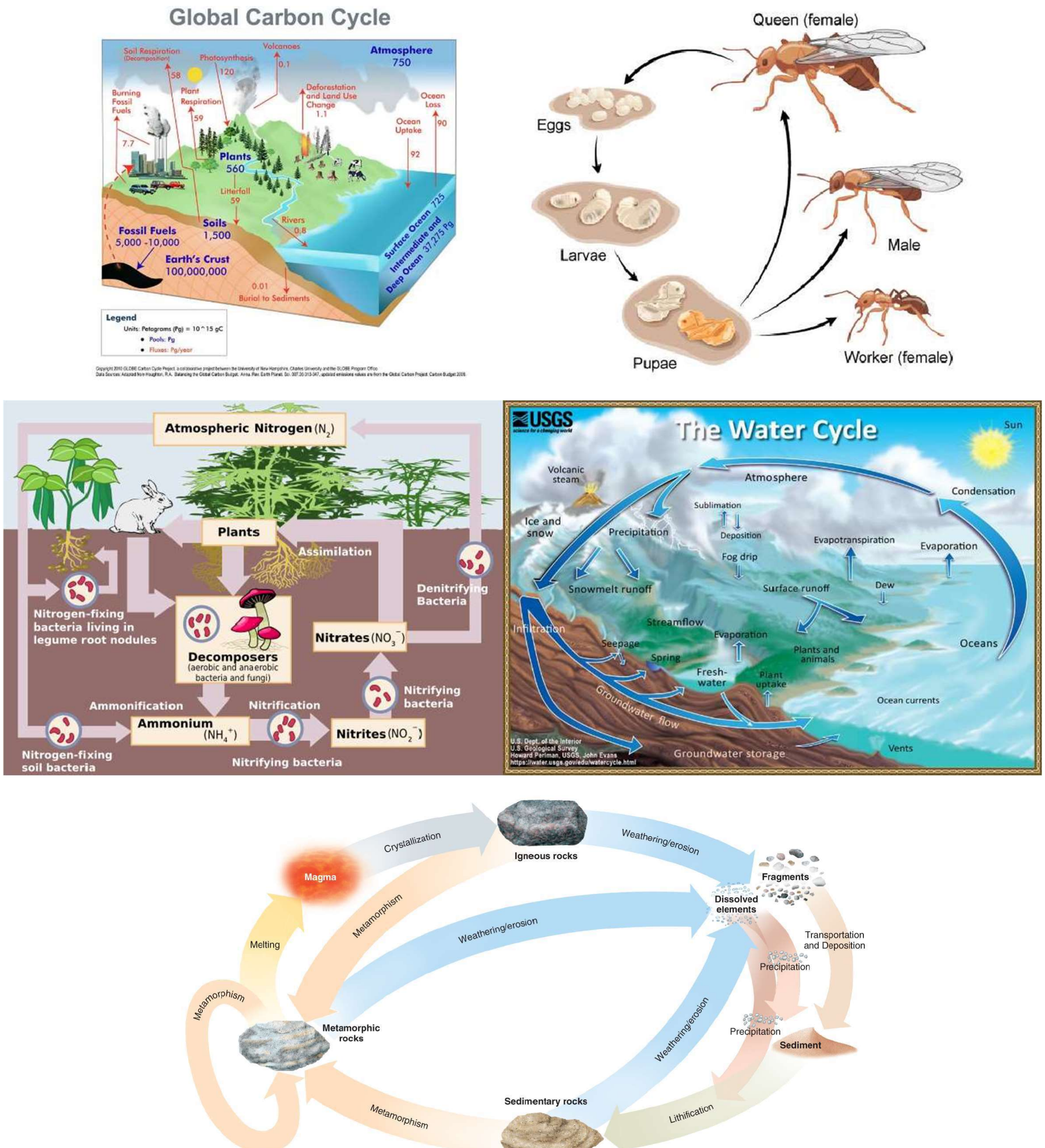


Figure 12.3. Some examples of cycles to aid in study of Earth's systems. From L to R, Top to Bottom: carbon cycle, life cycle of an ant, nitrogen cycle, water cycle, and rock cycle.

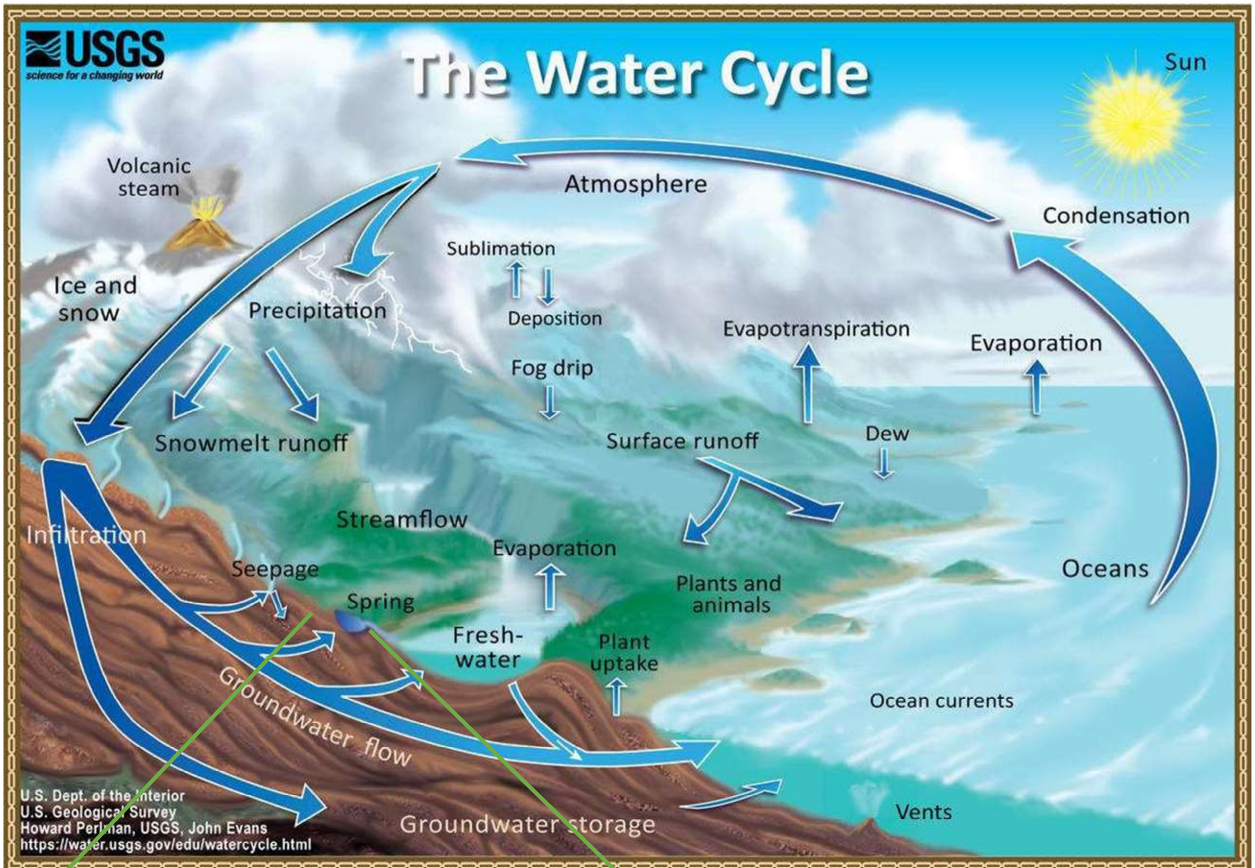


Figure 12.4. The water cycle (Evans and Perlman, 2014)

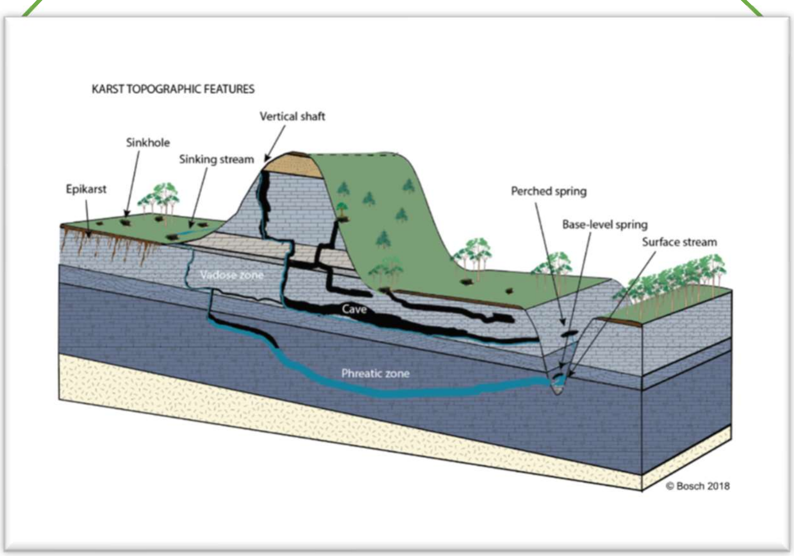


Figure 12.5. Karst topographic features (Bosch, 2018)

The above figure (12.4) is a graphical representation of the water cycle. Although the cycle has no beginning and no end, all water in earth's hydrosphere was originally released from magma as volcanic steam. Water is stored in the atmosphere, in glaciers, in oceans, and in rock (as groundwater). Within each portion of our hydrosphere, we can zoom in to find increasing complexity and cycles within the cycle. For example, see the karst block diagram on the left (Figure 12.5).

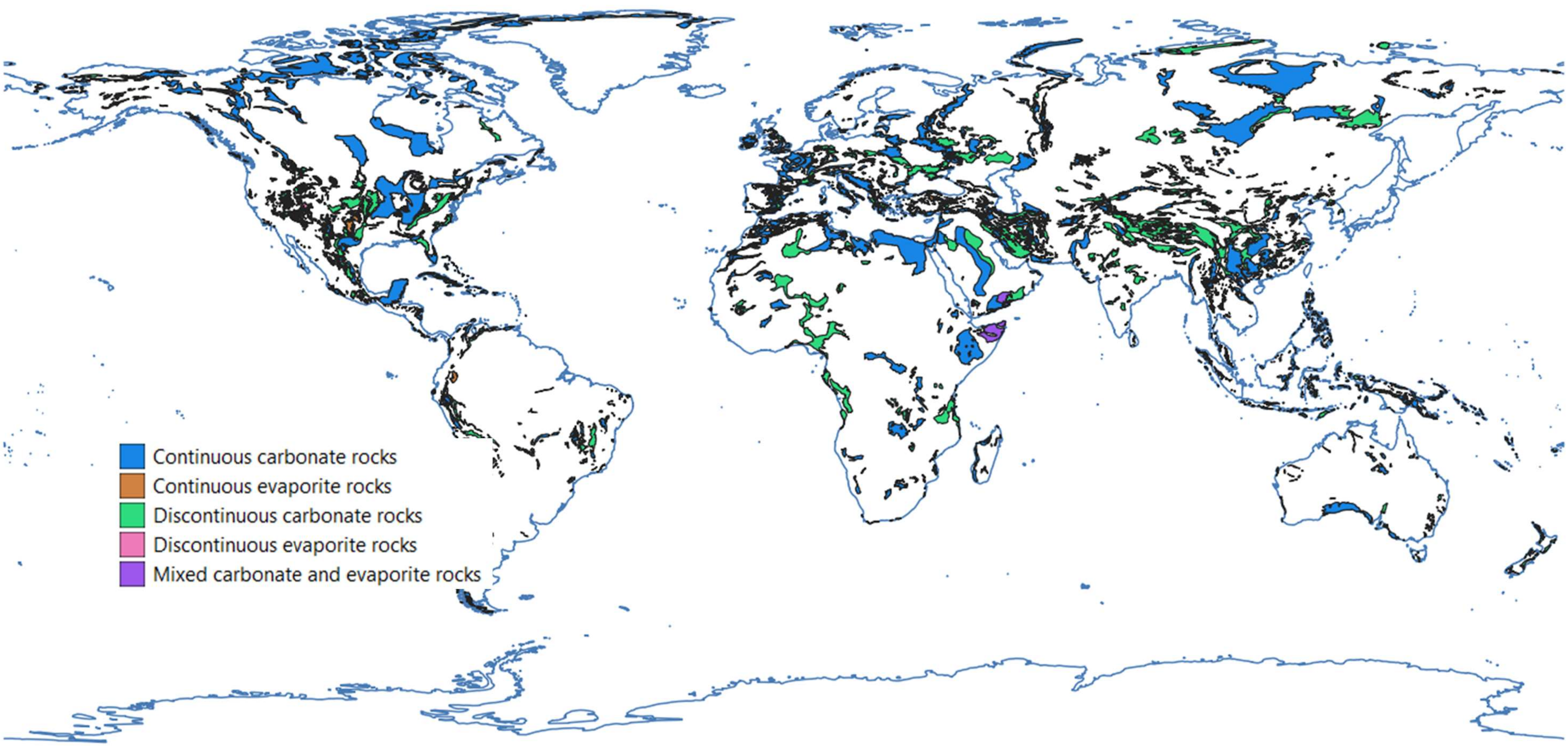
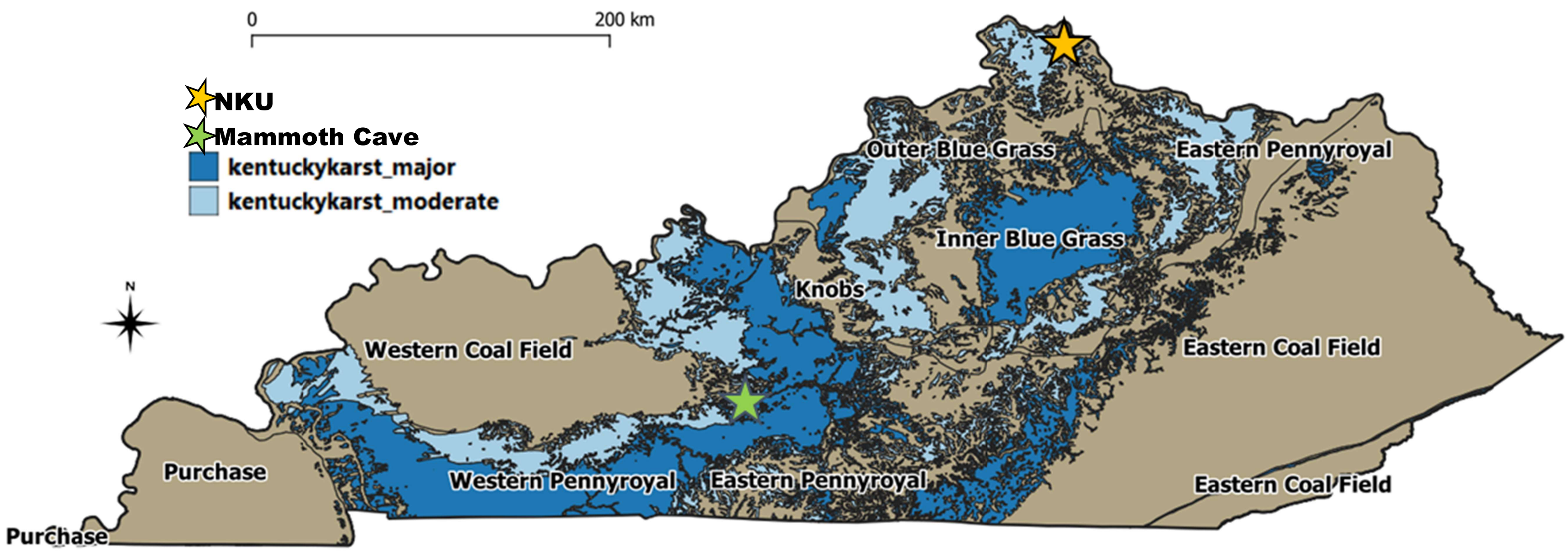


Figure12.6. World Karst Aquifer Map. Cartography in QGIS by author. data from Goldscheider, 2021 (https://www.whymap.org/whymap/EN/Maps_Data/Wokam/wokam_node_en.html; last access: 16 July 2021).

Kentucky Karst Map



Source: cartography in QGIS by author; data from Carey, 2002; Paylor and Currens, 2020, http://kgs.uky.edu/kgsweb/download/geology/karst500k.zip

FIELD TRIP: CINCINNATI MUSEUM CENTER
MUSEUM OF NATURAL HISTORY

PART I: Deep time globe

Walk into the Museum of Natural History and down the ramp through the dinosaur hall. At the end of the dinosaur exhibits is a large digital globe. Use the globe and the interactive story exhibits that go with it to answer the following questions.

1. Find northern Kentucky during the Ordovician period. What was this part of Earth like at that time?

2. What kind of sediments were being deposited then?

3. What rocks did these sediments lithify into?

4. Find central Kentucky during the Mississippian period. What was this part of Earth like at that time?

5. What kind of sediments were being deposited then?

6. What rocks did these sediments lithify into?

7. How are the Ordovician rocks in northern Kentucky and the Mississippian rocks in central Kentucky similar?

8. How are the Ordovician rocks in northern Kentucky and the Mississippian rocks in central Kentucky different?

9. The landscapes in these two regions are very different. Northern Kentucky has many creeks and rivers with stair-stepping knickpoints (waterfalls) while central Kentucky is a karst region with numerous extensive cave systems and very few surface streams. How do the differences in bedrock explain the differences in landscape?

PART II: Research at the Museum

Continue walking and you will find windows to two research labs: paleontology and genetics.

10. What projects are being worked on in these labs today?

PART III: Outside The Cave

There are several exhibits, videos, and displays outside The Cave. Explore these to answer the following questions.

11. How does karst fit into the water cycle?

12. What are some environmental concerns unique to karst landscapes?

13. Find an example of Mississippian rocks like those that are in central Kentucky. What fossils might you find in those rocks?

14. What was the depositional environment for those rocks?

15. Compare the age of the rocks to the age of the caves formed in those rocks.

16. How do limestone caves form?

PART IV: Into The Cave

When you are standing on the threshold of The Cave exhibit, there is a choice of which path to take. If you are willing and able, take the stairs down to the right. This will take you on a path that does of good job of simulating a caving experience. If you need to take the path to the left, it is physically less challenging, but has all the same educational content as the more challenging path.

17. Pause and look to your right just inside The Cave. What type of karst feature is modeled as the entrance to this cave system?

18. As you walk through the cave passage, note the shapes in the walls. These cuspate, asymmetrical, concave sculpted features that tessellate the wall are called scallops. In a limestone cave, how do you think they would form?

19. How can people infer the past conditions of a cave passage by examining scallops?

20. Find the decoration room. What features are modeled here?

21. In a limestone cave, how would these features form? (If you want more information about this, revisit one of the videos after you exit the cave.)

22. Find a vertical shaft in The Cave. How do you think these develop?

23. On your way out of the cave, you will see an exhibit of gypsum. How do gypsum minerals grow in caves?

24. Name three reasons why karst landscapes are vulnerable. Describe why and how these resources should be protected.

NOTES

Lab 13—Geographical Information Systems (GIS)

Activity A: Karst hydrogeology: a virtual field experience using © Google Earth, GIS, and TAK (Bosch, 2021)

A1 Summary

Students will have the opportunity to select and virtually explore the hydrogeology and geomorphology of a karst land-scape using © Google Earth, lidar-data-sourced DEM(s), and GIS software (QGIS) such that they gain an understanding of karst landscapes and their associated hazards, can access and analyze internet-based remote sensing data, and employ verbal and written communication of scientific information.

A2 Activity description

About 16.5 % of the world's population lives on karst (Goldscheider et al., 2020). It is therefore important that we under-stand the drainage patterns, potential hazards to humans, and potential threats to water quality that are unique to karst.

Prior to beginning this activity, download and install the following software packages: © Google Earth on web or desktop (https://www.google.com/earth/versions/; last access: 13 June 2021) and a GIS (QGIS is a free and open-source option; https://www.qgis.org/en/site/; last access: 13 June 2021).

1. Background – review background information on karst and on the source of the digital elevation model (DEM) data used in this activity.

Background information on karst is available from https: //link.springer.com/article/10.1007/s10040-016-1519-3 (last access: 13 June 2021), https://kgs.uky.edu/kgsweb/olops/pub/kgs/ic04_12.pdf (last access: 13 June 2021), https://en.wikipedia.org/wiki/Karst (last access: 13 June 2021), and http://www.igme.es/boletin/2016/127_1/BG_127-1_Art-9.pdf (last access: 13 June 2021).

Background on specific karst areas you can explore during this activity can be found at the following URLs:

- Central Kentucky Karst, USA, at https://www.usgs.gov/science-support/osqi/yes/national-parks/ mammoth-cave-national-park (last access: 13 June 2021), http://www.igme.es/boletin/2016/127_1/BG_127-1_Art-9.pdf (last access: 13 June 2021).
- El Sótano de las Golondrinas, Mexico, at http://www.mexicancaves.org/bul/bul2.pdf (last access: 13 June 2021)
- Caverna de Santana, Brazil, at https://en.wikipedia.org/wiki/Caverna_Santana (last access: 13 June 2021)
- Sof Omar Cave, Ethiopia, at https://en.wikipedia.org/wiki/Sof_Omar_Caves (last access: 13 June 2021)
- Postojna Cave, Slovenia, at https://www.postojnska-jama.eu/en/ (last access: 13 June 2021), https://www.slovenia.info/en/stories/karst (last access: 13 June 2021),

https://izrk.zrc-sazu.si/en/predstavitev (last access: 13 June 2021)

- Tenglong Cave, China, at https://en.wikipedia.org/wiki/Tenglong_Cave (last access: 13 June 2021)

- Waitomo Cave, New Zealand, at https://www. newzealand.com/us/waitomo-caves/ (last access: 13 June 2021), https://en.wikipedia.org/wiki/Waitomo_Glowworm_Caves (last access: 13 June 2021).

Background on the Shuttle Radar Topography Mission (SRTM) to acquire the data used in the DEMs recommended in this activity can be found at https://www2.jpl.nasa.gov/srtm/ (last access: 13 June 2021)

For an overview of karst aquifers on Earth, refer to the World Karst Aquifer Map (WOKAM), avail-able at https://www.whymap.org/whymap/EN/Maps_Data/Wokam/wokam_node_en.html (last access: 13 June 2021). Use the WOKAM to select an area of interest, browse © Google Earth to search for karst landforms, or use one of the following links to go directly to a karst area:

- Google Earth – Caverna de Santana, Brazil, available at https://earth.google.com/web/search/Caverna+de+Santana (last access: 13 June 2021).

- Google Earth – Central Kentucky Karst, USA, available at https://earth.google.com/web/search/Smiths+Grove (last access: 13 June 2021).

- Google Earth – El Sótano de las Golondrinas, Mexico, available at https://earth.google.com/web/search/Sotano+Golondrinas (last access: 13 June 2021).

- Google Earth – Postojna Cave, Slovenia, available at https://earth.google.com/web/search/Postojna+Cave (last access: 13 June 2021).

- Google Earth – Sof Omar Cave, Ethiopia, available at https://earth.google.com/web/search/Holqa (last access: 13 June 2021).

- Google Earth – Tenglong Cave, China, available at https://earth.google.com/web/search/Tenglong+Cave (last access: 13 June 2021).

- Google Earth – Waitomo Cave, New Zealand, available at https://earth.google.com/web/search/Waitomo+Cave (last access: 13 June 2021).

2. Data acquisition – acquire topographic information for your chosen karst landscape. For locations in the United States, EarthExplorer is a good source for SRTM DEM files (https://earthexplorer.usgs.gov/, last access: 13 June 2021). For sites outside of the USA, you can still find DEM data but may need to do additional internet searching to obtain it.

3. Data processing

   a. The DEM file then needs to be uploaded to a GIS. Check the properties of your DEM raster layer to see what CRS it is loaded in. For many DEMs, you will need to find the appropriate CRS and reproject the raster. For a review of the Universal Transverse

Mercator (UTM) system, consult the USGS fact sheet (https://pubs.usgs.gov/fs/2001/0077/report.pdf; last access: 13 June 2021) and a world map of UTM zones (https://maptools.com/tutorials/grid_zone_details; last access: 13 June 2021). Another option is to use an interactive online map (https://mangomap.com/robertyoung/maps/ 69585/what-utm-zone-am-i-in-; last access: 13 June 2021)to help determine the coordinate system for your location. The reproject task is performed by selecting the layer for the DEM raster data. Then click on the "raster" dropdown menu. Go to "Projections" and select "Warp (reproject). . . " Select a complete path for the output and give a name to the output file for the reprojected map data.

b. After the project is in the correct CRS, you can then choose a color scheme (right-clickon the layer > "properties" > "style" > "rendertype" > "singleband pseudocolor" > "generatea new color map" > select the desired color band > "classify") and make a Hillshade layerto better visualize the topography. To generate a Hillshade layer, use the "raster" menu again. Go to "Terrain analysis" > "Hillshade. . . ".
    i. Questions: what karst aquifer region did you select? What UTM zone is this field site in? What color band worked best for your visualization ofthe topography? What does the Hillshade function do? How is it helpful?

c. To better understand the drainage patterns of this landscape, extract a set of topographic contour lines. Open the "raster" menu. Go to "Extraction" > "Contour. . . " A good interval to start with is 20. If the contour lines end up looking too crowded or too spread out, you can make new con-tour layers with different intervals.

d. Now that you have detailed topographic maps withcontour intervals, you may want to revisit the ruleof V's for determining flow paths over land surfaces (https://d32ogoqmya1dw8.cloudfront.net/files/teachearth/activities/watercourses_ridges_topographic_maps_why_vs.pdf; last access: 13 June 2021). If you have access to a printer, you canprint out a paper copy of the map you built and draw the drainage patterns in with a pencil. There are two digital options for drawing in the water flow paths. For the first, you can export the image of their map in QGIS in a .png format. To do this, go to the "Project" menu and select "Save as Image. .. ", and then use a photo editor to drawflow paths on the map. If you have more GIS experience, you may want to work directly in the GIS and make new vector layers to create surface flow paths.
    i. Questions: describe the flow paths you drew onyour map. What challenges or obstacles did youencounter while determining the routes water would take?

Sharing science

- Write a formally structured report (including the title, author's name, date, introduction, methods, results, discussion, and conclusion). Within the report, or as a separate document, reflect on your experience with thisactivity and assess your level of understanding before and after the activity of (a) © Google Earth, (b) GIS, (c)UTM CRS, (d) topographic map interpretation, and (e)karst hydrogeology.

Activity B: Karst hydrogeology: a virtual field experience, alternate workflow using Google Earth, and the National Geologic Map Database project of the USGS

by Rachel Bosch, Northern Kentucky University; boschr1@nku.edu

B1 Summary

Students will have the opportunity to select and virtually explore the hydrogeology and geomorphology of a karst landscape using © Google Earth and the National Geologic Map Database project of the USGS such that they gain an understanding of karst landscapes and their associated hazards, can access and analyze internet-based remote sensing data, and employ written communication of scientific information.

B2 Activity description

About 16.5 % of the world's population lives on karst (Goldscheider et al., 2020). It is therefore important that we understand the drainage patterns, potential hazards to humans, and potential threats to water quality that are unique to karst.

1. Background – review background information on karst

Background information on karst is available from https://link.springer.com/article/10.1007/s10040-016-1519-3 (last access: 13 June 2021), https://kgs.uky.edu/kgsweb/olops/pub/kgs/ic04_12.pdf (last access: 13 June 2021), https://en.wikipedia.org/wiki/Karst (last access: 13 June 2021), and http://www.igme.es/boletin/2016/127_1/BG_127-1_Art-9.pdf (last access: 13 June 2021).

Background on specific karst areas you can explore during this activity can be found at the following URLs:

– Central Kentucky Karst, USA, at https://www.usgs.gov/science-support/osqi/yes/national-parks/mammoth-cave-national-park (last access: 13 June 2021), http://www.igme.es/boletin/2016/127_1/BG_127-1_Art-9.pdf (last access: 13 June 2021)
– El Sótano de las Golondrinas, Mexico, at http://www.mexicancaves.org/bul/bul2.pdf (last access: 13 June 2021)
– Caverna de Santana, Brazil, at https://en.wikipedia.org/wiki/Caverna_Santana (last access: 13 June 2021)
– Sof Omar Cave, Ethiopia, at https://en.wikipedia.org/wiki/Sof_Omar_Caves (last access: 13 June 2021)
– Postojna Cave, Slovenia, at https://www.postojnska-jama.eu/en/ (last access: 13 June 2021), https://www.slovenia.info/en/stories/karst (last access: 13 June 2021), https://izrk.zrc-sazu.si/en/predstavitev (last access: 13 June 2021)
– Tenglong Cave, China, at https://en.wikipedia.org/wiki/Tenglong_Cave (last access: 13 June 2021)
– Waitomo Cave, New Zealand, at https://www.newzealand.com/us/waitomo-caves/ (last access: 13 June 2021), https://en.wikipedia.org/wiki/Waitomo_Glowworm_Caves (last access: 13 June 2021).

For an overview of karst aquifers on Earth, refer to the World Karst Aquifer Map (WOKAM), available at https://www.whymap.org/whymap/EN/Maps_Data/Wokam/wokam_node_en.html (last access: 13 June 2021). Use the WOKAM to select an area of interest, browse © Google Earth to search for karst landforms, or use one of the following links to go directly to a karst area:

– Google Earth – Caverna de Santana, Brazil, available at https://earth.google.com/web/search/Caverna+de+Santana (last access: 13 June 2021).
– Google Earth – Central Kentucky Karst, USA, available at https://earth.google.com/web/search/Smiths+Grove (last access: 13 June 2021).
– Google Earth – El Sótano de las Golondrinas, Mexico, available at https://earth.google.com/web/search/Sotano+Golondrinas (last access: 13 June 2021).
– Google Earth – Postojna Cave, Slovenia, available at https://earth.google.com/web/search/Postojna+Cave (last access: 13 June 2021).
– Google Earth – Sof Omar Cave, Ethiopia, available at https://earth.google.com/web/search/Holqa (last access: 13 June 2021).
– Google Earth – Tenglong Cave, China, available at https://earth.google.com/web/search/Tenglong+Cave (last access: 13 June 2021).
– Google Earth – Waitomo Cave, New Zealand, available at https://earth.google.com/web/search/Waitomo+Cave (last access: 13 June 2021).

2. Data acquisition – acquire topographic information for your chosen karst landscape.
To access a map, go to the topoView interface (Links to an external site: https://ngmdb.usgs.gov/topoview/viewer/#4/39.98/-100.06) for the National Geologic Map Database project of the USGS. Click on the map of the United States in an area that interests you. A list of available maps should appear on the right-hand side of the screen. Above the list, click on "date" to display the newest maps at the top. Select and download a recent map that you would like to use for this lab.
Additionally, the USGS has created a great tutorial video (with embedded closed-captioning) for how to access topographical maps from a mobile device (https://www.usgs.gov/media/videos/using-us-topo-and-historic-topo-maps-your-mobile-device; last access: 13 June 2021).

3. Data analysis—where does the water flow?
Now that you have detailed topographic maps with contour intervals, you may want to revisit the rule of V's for determining flow paths over land surfaces (see linked pdf). If you have access to a printer, you can print out a paper copy of the map and draw the drainage patterns in with a pencil. If you prefer, you may use an image of the map in a photo editor (or other tool of preference) to digitally draw flow paths on the map.

4. Sharing your science
Write a formally structured report (including the title, author's name, date, introduction, methods, results, discussion, and conclusion).
Be sure to address the following questions in your report:

- What karst aquifer region did you select?
- Where is this region located?
- What is the climate of this region?
- Why is this location a significant karst region?
- Who lives in this region?
- Describe the flow paths you drew on your map.
- What challenges or obstacles did you encounter while determining the routes water would take?
- Reflect on your experience with this activity and assess your level of understanding before and after the activity of (a) © Google Earth, (b) topographic map interpretation, and (c) karst hydrogeology.

NOTES

Lab 14—Glaciers

The Life of a Glacier (https://nsidc.org/cryosphere/glaciers, 2020)

Most of the world's glaciers are found near the poles, but glaciers exist on all of the world's continents, even Africa. Australia does not have any glaciers; however, it is considered part of Oceania, which includes several Pacific island chains and the large islands of Papua New Guinea and New Zealand. Both of these countries have glaciers.

Glaciers require very specific climatic conditions. Most are found in regions of high snowfall in winter and cool temperatures in summer. These conditions ensure that the snow that accumulates in the winter is not lost during the summer. Such conditions typically prevail in polar and high alpine regions.

The amount of precipitation, whether in the form of snowfall, freezing rain, avalanches, or wind- drifted snow, is important to glacier survival. For instance, in very dry parts of Antarctica, low temperatures are ideal for glacier growth, but the small amount of net annual precipitation causes the glaciers to grow very slowly, or even to disappear due to evaporation of the ice (sublimation).

Growing years


Chickamin Glacier, bounded by mountains on both sides, flows past a cabin in this photograph. Chickamin Glacier is located in the coastal mountains shared by southeast Alaska and British Columbia, Canada. —Credit: Photograph by J. C. Reed. 1941. Chickamin Glacier: From the Glacier Photograph Collection. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

A glacier forms when snow accumulates over time, turns to ice, and begins to flow outwards and downwards under the pressure of its own weight. In polar and high-altitude alpine regions, glaciers generally accumulate more snow in the winter than they lose in the summer from melting, evaporation, or calving. If the accumulated snow survives one melt season, it forms a denser, more compressed layer called firn. The snow and firn are further compressed by overlying snowfall, and the buried layers slowly grow together to form a thickened mass of ice.

Each year's new snowfall continues to compact the underlying layers, and the snow grains become larger ice crystals randomly oriented in connected air spaces. These ice crystals can eventually grow to become several centimeters in diameter.

As compression continues and the ice crystals grow, the air spaces in the layers decrease, becoming small and isolated. This compaction compresses more air spaces out of the snowpack and compacts the remaining air into bubbles. At greater depth (hundreds of meters) the air in these bubbles is squeezed into the crystal structure of the ice. Thus dense glacial ice has no air bubbles, but contains trapped air nevertheless.

Moving forward

Under the pressure of its own weight and the forces of gravity, a glacier will begin to move, or flow, outwards and downwards. Valley glaciers flow down valleys, and continental ice sheets flow outward in all directions.

Glaciers move by internal deformation of the ice, and by sliding over the rocks and sediments at the base. Internal deformation occurs when the weight and mass of a glacier causes it to spread out due to gravity. Sliding occurs when the glacier slides on a thin layer of water at the bottom of the glacier. This water may come from glacial melting due to the pressure of the overlying ice or from water that has worked its way through cracks in the glacier. Glaciers can also readily slide on a soft sediment bed that has some water in it. This is known as basal sliding and may account for most of the movement of thin, cold glaciers on steep slopes or only 10 to 20 percent of the movement of warm, thick glaciers lying on gentle slopes.

When a glacier moves rapidly around a rock outcrop or over a steep area in the bedrock, internal stresses build up in the ice. These stresses can cause cracks, or crevasses, on the glacier surface.

In retreat

LeConte Glacier flows into a bay on the coast of Alaska. Since its discovery, the glacier has retreated about 4 kilometers (2.5 miles). —Credit: Photograph by U.S. Navy. 1929. LeConte Glacier: From the Glacier Photograph Collection. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Glacial retreat, melt, and ablation result from increasing temperature, evaporation, and wind scouring. Ablation is a natural and seasonal part of glacier life. As long as snow accumulation equals or is greater than melt and ablation, a glacier will remain in balance or even grow. Once winter snowfall decreases, or summer melt increases, the glacier will begin to retreat

As they flow, glaciers plow up or push aside rocks and debris, which is then left behind when the glacier recedes. Then, as large glaciers retreat, the underlying ground surface is typically abraded of most materials, leaving only scars and debris on the underlying bedrock surface.

Over the past 60 to 100 years, glaciers worldwide have tended to retreat. Alpine glaciers, which are typically smaller and less stable to begin with, seem particularly susceptible to retreat. Over 90 percent of the measured alpine glaciers in the world are retreating, in almost every major glaciated region. The causes of this widespread retreat are varied, but the underlying primary causes are a warming climate and the effects of increased soot and dust in areas of higher agricultural and industrial activity.

What are the components of a glacier?

(https://nsidc.org/cryosphere/glaciers, 2019)

Crevasses rumple the surface of Crane Glacier in Antarctica. —Credit: Ted Scambos, NSIDC

Glaciers are dynamic, and several elements contribute to glacier formation and growth. Snow falls in the accumulation area, usually the part of the glacier with the highest elevation, adding to the glacier's mass. As the snow slowly accumulates and turns to ice, and the glacier increases in weight, the weight begins to deform the ice, forcing the glacier to flow downhill. Further down the glacier, usually at a lower altitude, is the ablation area, where most of the melting and evaporation occur. Between these two areas a balance is reached, where snowfall equals snowmelt, and the glacier is in equilibrium. Whenever this equilibrium is disturbed, either by increased snowfall or by excessive melting, the glacier either advances or retreats at more than its normal pace.

The Aletsch Glacier in Switzerland has a prominent moraine on its surface. —Credit: Photograph by Harry Fielding Reid. 1902. Aletsch Glacier: From the Glacier Photograph Collection. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Several visible features are common to most glaciers. At locations where a glacier flows rapidly, friction creates giant cracks called crevasses, which may make travel across a glacier treacherous. Other common glacial features are moraines, created when the glacier pushes or carries rocky debris as it moves. These long, dark bands of debris are visible on top and along the edges of glaciers. Medial moraines run down the middle of a glacier, lateral moraines along the sides, and terminal moraines are found at the terminus, of a glacier. Sometimes one glacier flows into another, creating combined wider moraines. Often these linear deposits of rocks are left behind, almost intact, after the ice in a glacier has melted away. Studying these rocky debris remnants, and the sediments that were once beneath the glacier, is the subject of glacial geology and geomorphology.

PART I: An introduction to glacial dynamics

(Cesta and Orr, 2018)

Objectives: Develop a deeper understanding of glacial motion by conducting a physical experiment emulating alpine glaciation.

Outcomes: By the end of the activity, you will be able to 1) explain how ice flows within an alpine glacier, 2) quantitatively describe ice motion and glacial metrics (e.g. velocity, discharge), 3) begin to discuss how alpine glaciers respond to changing environmental conditions, and 4) evaluate the successes and shortcomings of using physical models to understand glacier dynamics.

<u>Activity Instructions</u>

Please make sure that you read the activity instructions fully before you begin. The physical model has been set up prior to class for you.

Equipment list: Glacier goo, ruler, PVC pipe, pencil, timer, calculator and stack of books.

1) You are required to measure the velocity and discharge of your glacier over a two-minute period. Discuss with your group the best way of calculating these metrics. The following equations may prove useful:

$$\bar{u} = {}^{\Delta x}/_{t} \tag{1}$$

where:
$\bar{u}$ = average velocity
Δx = change in distance
t = time

$$Q = A\bar{u} \tag{2}$$

where:
Q = discharge
$\bar{u}$ = average velocity
A = cross-sectional area

$$A = \tfrac{1}{2}\pi r^2 \tag{3}$$

where:
A = area of a half-circle
r = radius of the pipe

we will assume that the glacier fills the full half of the PVC pipe. Think about how this may bias the calculations you will make during the lab

2) Using your physical model, measure the velocity and discharge of your glacier over 2 minutes. Record your results in the table blow. The column names may offer some clues about what measurements you will need to complete this exercise. ** *note the units!!* **

Group Name	1) Glacier dimensions			2) Glacier motion			3) Equivalent Velocities		
	Depth (cm)	Width (cm)	Cross sectional area (cm^2)	Distance travelled by glacier (cm)	Velocity (cm/min)	Discharge (cm^3/min)	(m/min)	(m/hr)	(m/yr)

3) In your group consider the following questions whilst you conduct your experiment:
- How does velocity vary across the glacial valley? How does it vary with depth? What observations did you make to conclude this?

- What is influencing the glacier's velocity? What might increase/decrease your measurements?

- If the PVC pipe was lined with a different substrate (e.g., sandpaper) how might the velocity and discharge of the glacier change?

- How well does this physical model emulate the real-world system? What is realistic/unrealistic about the model? What aspects of the glacial system does this analog model?

PART II: Glacial Geology of Ohio (Ward, 2017)

Look at the Glacial Map of Ohio and read the information page about the glacial deposits of Ohio.

1. Define the following terms from the map legend and describe how they relate to a glacier or ice sheet. You may use your lab manual, Wikipedia, or your classmates for help.

Moraine:

Esker:

Outwash:

Peat:

Colluvium:

2. Find the oldest deposits on the map. Where are they? How old are they? To which *glacial stage* do they belong?

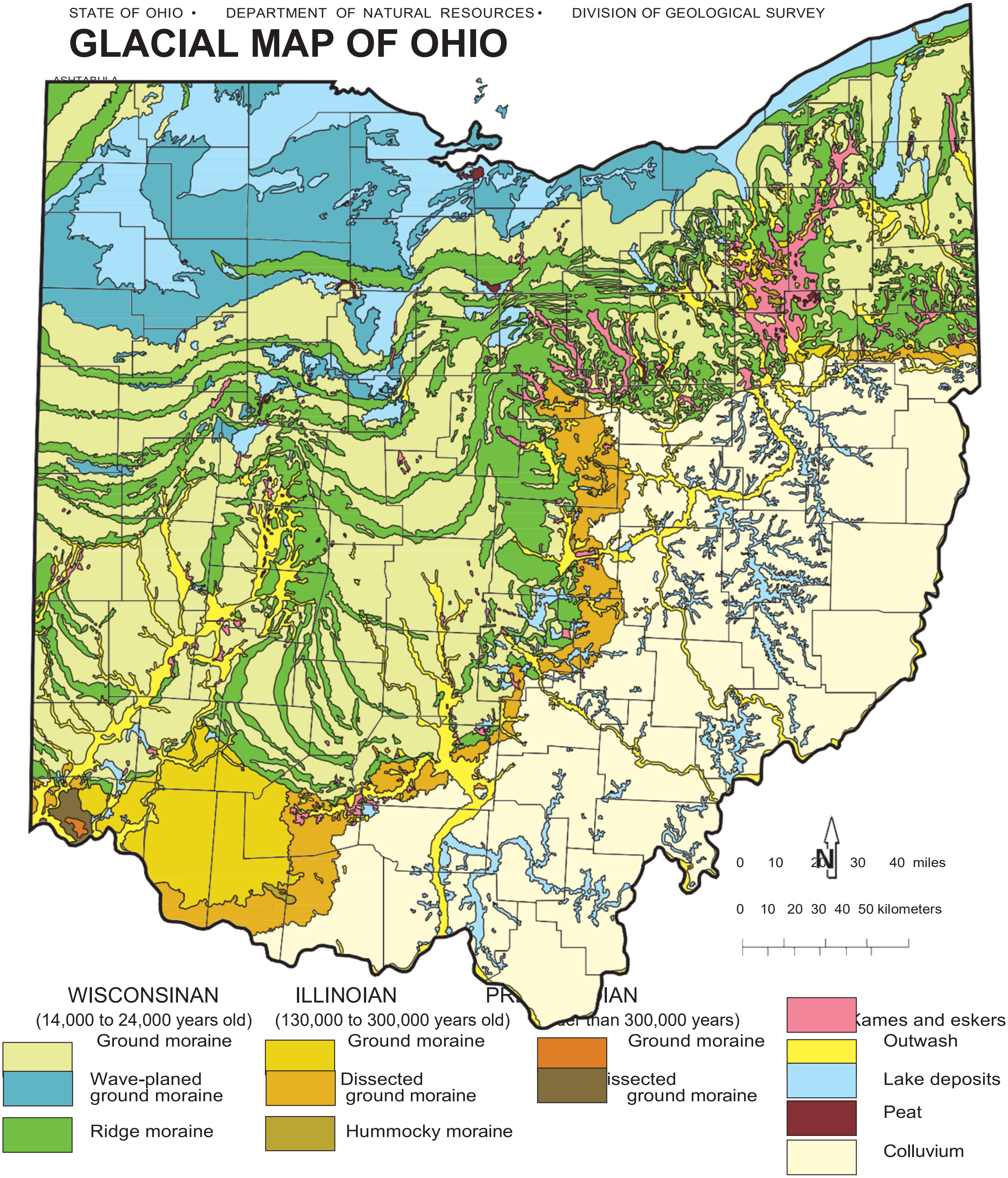
3. Draw a line on the map outlining the southern extent of Wisconsinan stage glacial deposits. This is where the terminus of the ice sheet was located about 20,000 years ago.

4. Was the Illinoian stage ice sheet larger or smaller than the Wisconsinan stage ice sheet? How can you tell?

5. List several reasons why the ice sheet may have been larger during one stage than during another.

6. On the map, find the Wisconsinan-stage ridge moraines and number them (1,2,3,…) from oldest to youngest, starting with 1 as the oldest moraine.

7. What does this sequence of moraines represent?



Recommended citation: Ohio Division of Geological Survey, 2005, Glacial map of Ohio: Ohio Department of Natural Resources, Division of Geological Survey, page-size map with text, 2 p., scale 1:2,000,000.

GLACIAL DEPOSITS OF OHIO

Although difficult to imagine, Ohio has at various times in the recent geologic past (within the last 1.6 million years) had three-quarters of its surface covered by vast sheets of ice perhaps as much as 1 mile thick. This period of geologic history is referred to as the Pleistocene Epoch or, more commonly, the Ice Age, although there is abundant evidence that Earth has experienced numerous other “ice ages” throughout its 4.6 billion years of existence.

Ice Age glaciers invading Ohio formed in central Canada in response to climatic conditions that allowed massive buildups of ice. Because of their great thickness, these ice masses flowed under their own weight and ultimately moved south as far as northern Kentucky. Oxygen-isotope analysis of deep-sea sediments indicates that more than a dozen glaciations occurred during the Pleistocene. Portions of Ohio were covered by the last two glaciations, known as the Wisconsinan (the most recent) and the Illinoian (older), and by an undetermined number of pre-Illinoian glaciations.

Because each major advance covered deposits left by the previous ice sheets, pre-Illinoian deposits are exposed only in extreme southwestern Ohio in the vicinity of Cincinnati. Although the Illinoian ice sheet covered the largest area of Ohio, its deposits are at the surface only in a narrow band from Cincinnati northeast to the Ohio-Pennsylvania border. Most features shown on the map of glacial deposits of Ohio are the result of the most re- cent or Wisconsinan-age glaciers.

The material left by the ice sheets consists of mixtures of clay, sand, gravel, and boulders in various types of deposits of different modes of origin. Rock debris carried along by the glacier was deposited in two principal fashions, either directly by the ice or by meltwater from the glacier. Some material reaching the ice front was carried away by streams of meltwater to form outwash deposits. Material deposited by water on and under the surface of the glacier itself formed features called kames and eskers, which are recognized by characteristic shapes and composition. A distinctive characteristic of glacial sediments that have been deposited by water is that the material was sorted by the water that carried it. Thus, outwash, kame, and esker deposits normally consist of sand and gravel. The large boulder-size particles were left behind and the smaller clay-size particles were carried far away, leaving the intermediate gravel- and sand-size material along the stream courses.

Material deposited directly from the ice was not sorted and ranges from clay to boulders. Some of the debris was deposited as ridges parallel to the edge of the glacier, forming terminal or end moraines, which mark the position of the ice when it paused for a period of time, possibly a few hundred years. When the entire ice sheet receded because of melting, much of the ground-up rock material still held in the ice was deposited on the surface as ground moraine. The oldest morainic deposits in Ohio are of Illinoian and pre-Illinoian age. Erosion has significantly reduced these deposits along the glacial boundary, leaving only isolated remnants that have been mapped as dissected ground moraine and hummocky moraine.

Many glacial lakes were formed in Ohio during the Ice Age. Lake deposits are primarily fine-grained clay- and silt-size sediments. The most extensive area of lake deposits is in northern Ohio bordering Lake Erie. These deposits, and adjacent areas of wave-planed ground moraine, are the result of sedimentation and erosion by large lakes that occupied the Erie basin as Wisconsinan-age ice retreated into Canada. Other lake deposits accumulated in stream valleys whose outlets were temporarily dammed by ice or outwash. Many outwash-dammed lake deposits are present in southeastern Ohio far beyond the glacial boundary. Peat deposits are associated with many lake deposits and formed through the accumulation of partially decayed aquatic vegetation in oxygen-depleted, stagnant water.

The term glacial drift commonly is used to refer to any material deposited directly (*e.g.*, ground moraine) or indirectly (*e.g.*, outwash) by a glacier. Because the ice that invaded Ohio came from Canada, it carried in many rock types not found in Ohio. Pebbles, cobbles, and boulders of these foreign rock types are called erratics. Rock collecting in areas of glacial drift may yield granite, gneiss, trace quantities of gold, and very rarely, diamonds. Most rocks found in glacial deposits, however, are types native to Ohio.

Certain deposits left behind by the ice are of economic importance, particularly sand and gravel, clay, and peat. Sand and gravel that have been sorted by meltwater generally occur as kames or eskers or as outwash along major drainageways. Sand and gravel are vital to Ohio’s construction industry. Futhermore, outwash deposits are among the state’s most productive sources of ground water. Glacial clay is used in cement and for common clay products (particularly brick). The minor quantities of peat produced in the state are used mainly for mulch and soil conditioning.

PART III: ***Investigation:*** *Glaciers and Climate Change Case Study—Grinnell Glacier, Montana* (adapted from Ormand, 2010).

Team member names:

Introduction: Glaciers are ephemeral climate-related features that dramatically imprint the shape of the landscape over time. This investigation examines the historical changes to Grinnell Glacier in Glacier National Park, Montana (Fig. 14.2). Grinnell Glacier is one of the largest remaining glaciers in the park, even though it is less than a square mile in area. In this investigation, we’ll estimate how long it will be before there are no longer glaciers in Glacier National Park, based on historical records.

Historical Field Mapping: First measurements of glaciers in Glacier National Park were conducted as part of topographic field mapping in 1900. From the early 1900's to the 1960's, several scientists working with the National Park Service created a photographic archive of glaciers, with re-surveying on a regular basis throughout the 1900's. See the attached map (Fig. 14.1) showing the position of the glacial front historically during the early and mid-1900's (The map is from U. S. Geological Survey Professional Paper 1180: Grinnell and Sperry Glaciers, Glacier National Park, Montana: a Record of Vanishing Ice, published by the USGS in 1980).

Part I: Initial Observations and Predictions

Consider the map in Figure 4.1, showing the areas Grinnell Glacier covered in 1850, 1937, 1968, and 1993, and the glacial front positions for 1887, 1937, 1946, 1960, and 1968. Based on only this evidence, answer the following questions:

- Has this glacier been advancing or retreating over time? What factors control glacial advance and retreat?
- Approximately how many years do you think it will be until Grinnell Glacier is completely melted? How did you produce your estimate?

Part II: Data collection

Divide into four teams. Each group will choose a year (1850, 1937, 1968, or 1993). Using the map in Figure 14.1, note the outline of the extent of Grinnell Glacier for your year. Then carefully cut out your glacier outline. Trace it onto the graph paper provided. Then count the number of squares of graph paper contained within your traced outline. Count every full square and any square that is more than halfway in your traced outline. The total should be very close to the surface area of Grinnell Glacier that year, in "squares." But how big is each square of your graph paper? Compare the squares of the graph paper to the map scale. Convert your counted area to a more practical unit of measurement. Determine the following:

Year of glacial front used in analysis: ___________

Total number of graph squares in glacial area ___________

Map scale of Figure 2: 1 inch on map = _________ meters on ground

  1 square inch on map = ___________ square meters on the ground

  Number of graph squares per square inch = ___________

  Number of square meters per graph square = ___________

Total scaled area of active glacier for your year in square meters: __________

Total scaled area of active glacier for your year in square kilometers: __________

Distance of glacial front in your year, from upper most elevation of ice (m) __________

Distance of glacial front in your year, from upper most elevation of ice (km) __________

Sharing data with other teams, complete this table on the whiteboard.

Year	Area of active glacier (m^2)	Area of active glacier (km^2)	Distance of front from origin (km)
1850			
1937			
1968			
1993			

Part III: Analysis

Using Excel, another favorite software package, or hand graphing techniques, create the following graphs:
Active Glacier Area (Y-axis) vs. Year (X-axis)
Distance of Front (Y-axis) vs. Year (X-axis)

Part V: Interpretation

Now, it's time to revisit the question posed in Part I: Approximately how many years do you think it will be until Grinnell Glacier is completely melted? In the discussion of your data, provide a linkage between your observations at Grinnell Glacier, and the historic global atmospheric temperature data depicted in the graph on Figure 14.3. How do your results fit with the context of global climate change and possible causes for historic glacial retreat? What are long-term implications from glacial analysis at Glacier National Park, Montana?

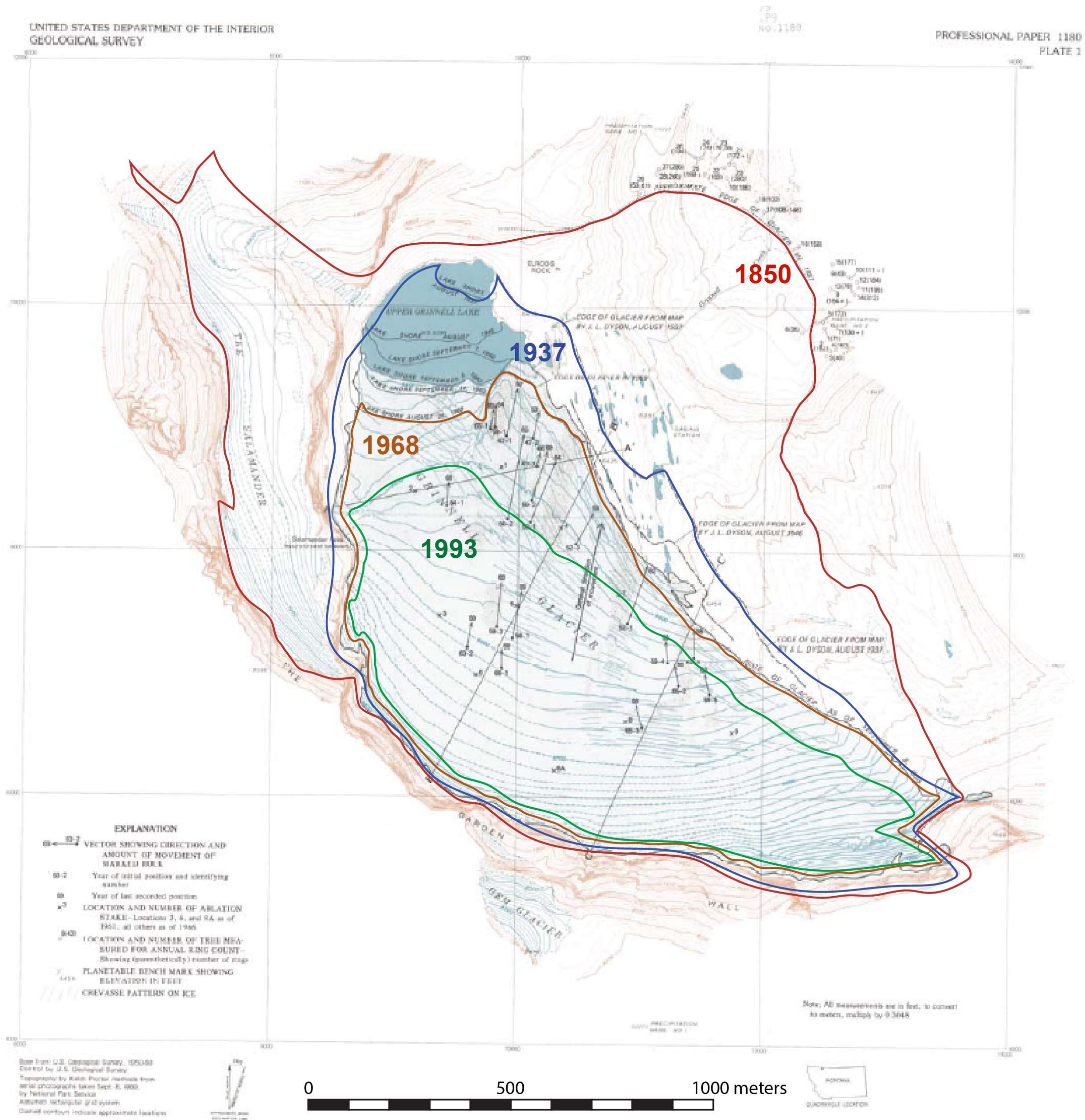


Figure 2. Map showing historical extents of Grinnell Glacier, Glacier National Park, Montana, USA

Figure 14.1. Map showing historical extents of Grinnell Glacier, Glacier National Park, Montana, USA.

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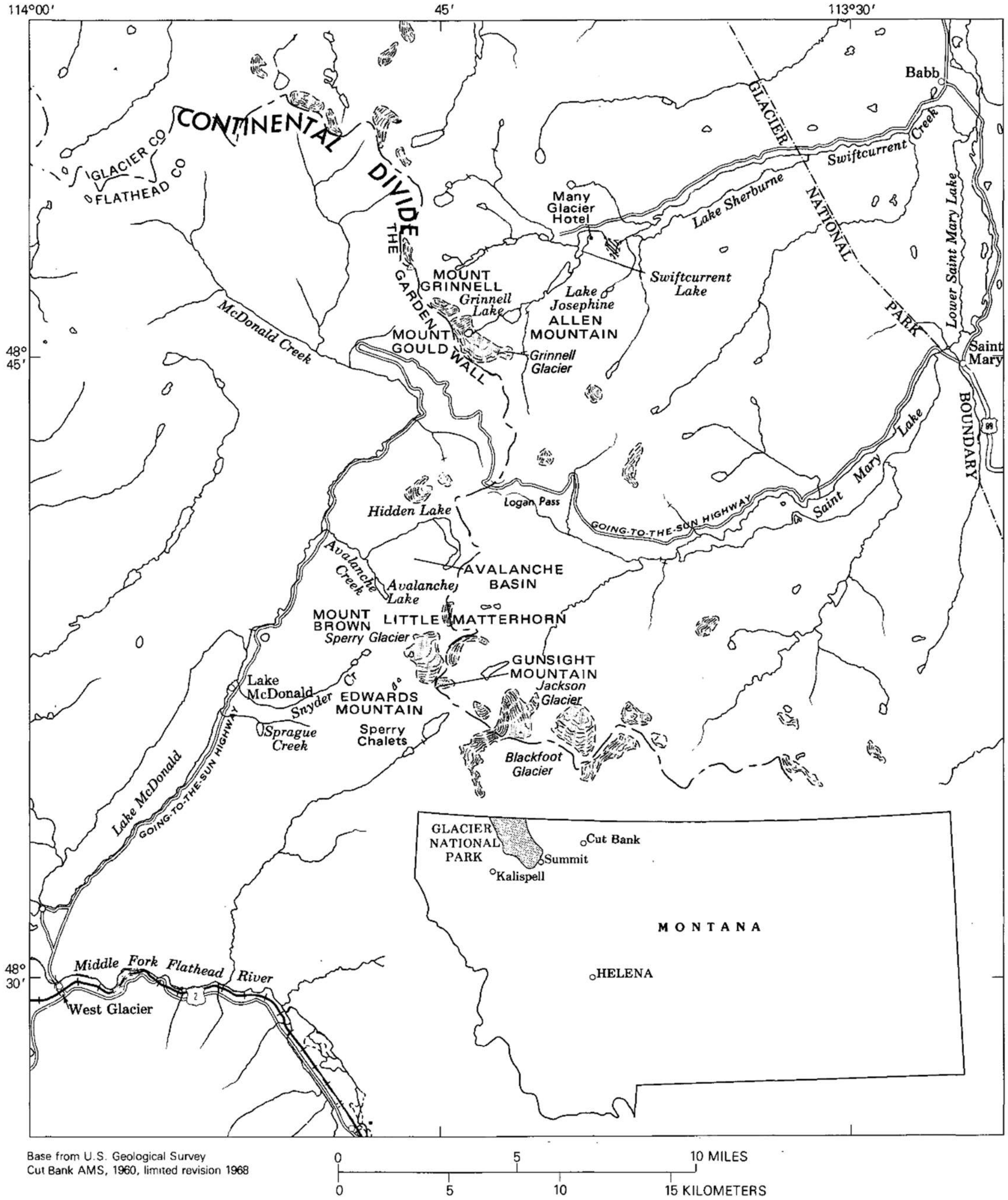


FIGURE 1.—Index map of the central part of Glacier National Park, Mont., showing location of Grinnell and Sperry Glaciers. Base from U.S. Geological Survey Cut Bank 1° x 2° quadrangle map, 1960–68.

Figure 14.2. Index map of the central part of Glacier National Park, Montana, showing location of Grinnell Glacier, from Johnson, A, 1980: *Grinnell and Sperry Glaciers, Glacier National Park, Montana: A record of vanishing ice*. No. 1180. US Government Printing Office.

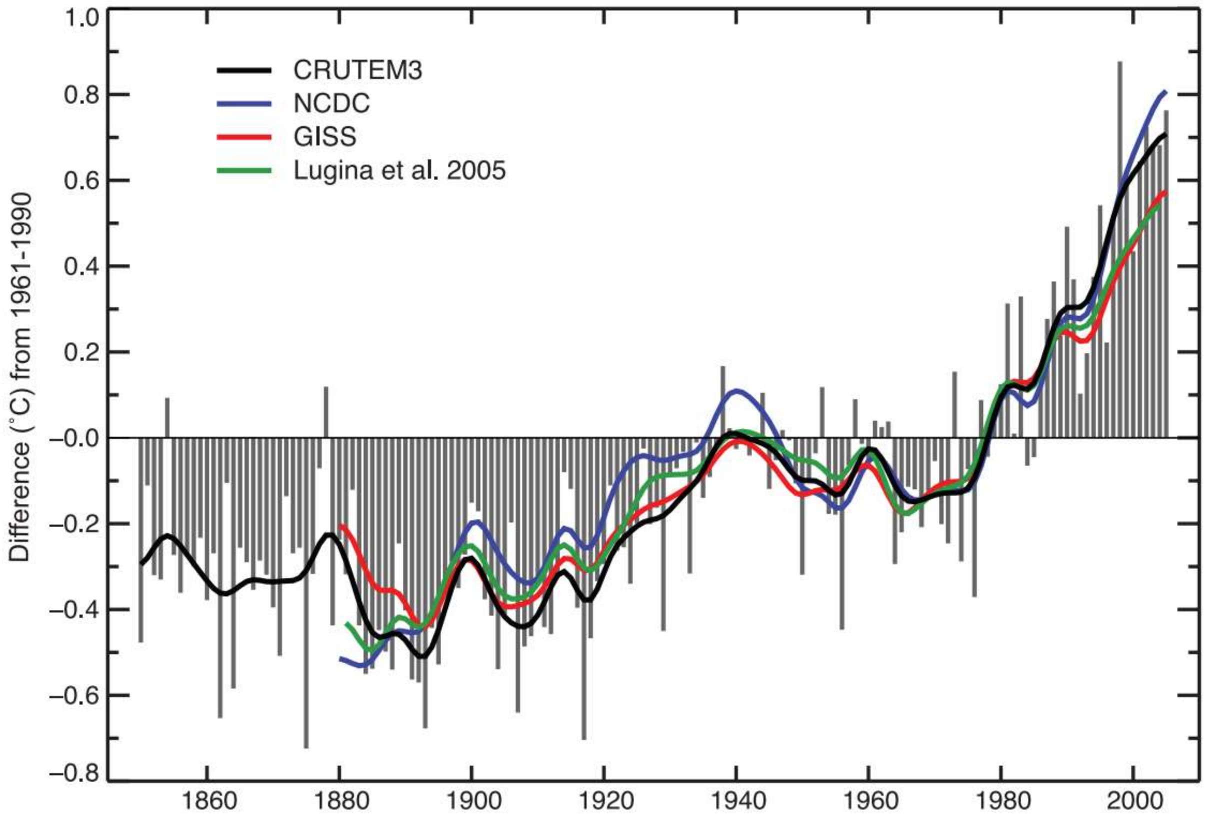


Figure 14.3. Annual anomalies of global land-surface air temperature (°C), 1850 to 2005, relative to the 1961 to 1990 mean for CRUTEM3 updated from Brohan et al. (2006). The smooth curves show decadal variations (see Appendix 3.A). The black curve from CRUTEM3 is compared with those from NCDC (Smith and Reynolds, 2005; blue), GISS (Hansen et al., 2001; red) and Lugina et al. (2005; green) from Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden and P. Zhai, 2007: Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

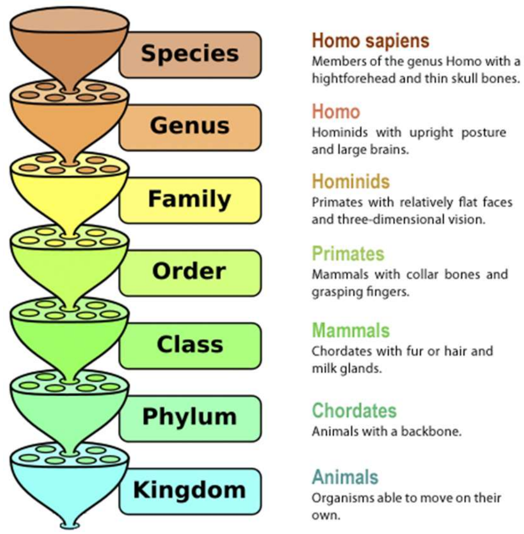
NOTES

NOTES

Lab 15—Planetary Science

(Adapted from Anderson, J.L.B., 2020, Lab 7 for GEOS 105 at Winona State University)

Throughout this lab you may want to refer to NASA's website about our Solar System: https://solarsystem.nasa.gov/solar-system/our-solar-system/overview/ (last access: 2021-11-26).



Where did all the objects in our Solar System come from?

Here we sit on the Earth, orbiting around a medium-sized star with a number of other objects. What happened, 4.5 billion years ago, that resulted in the formation of our Solar System?

When scientists approach a question like this about the natural world, we start by trying to classify whatever it is that we are examining. Scientists like to put objects into groups that might have common chemistry or a common history and evolution. For example, we put animals into groups using the Linnaean System and this helps us understand how these animals function, live, and how they evolved.

Your goal in lab this week is to examine how astronomers have classified the objects in our solar system.

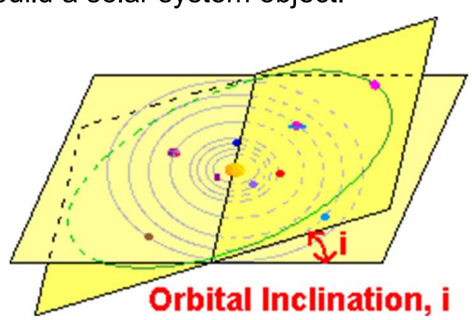
There are lots of way to classify a group of objects. For example, in classifying animals, we could classify them by how tall they are or how many legs they have or how well they can see. However, this wouldn't be a scientifically useful classification scheme. While there are a number of ways to classify the objects in our solar system, we typically look at an object's chemical composition and its orbital properties.

Chemical Composition—what type of materials is a given object made of?

Think about baking a cake—there are some common materials that you will almost always use such as flour, sugar, eggs, baking soda, salt, etc. When making a solar system, we also have common materials that are just floating around the galaxy in clouds of gas and dust including Hydrogen and Helium gas, little bits of dust (tiny rock particles), Ices (water, methane, ammonia), and Iron metal (Fe). Different proportions of each of these initial ingredients is what can be used to build a solar system object.

Orbital Properties—how "well-behaved" is an object's orbit?

How does a given object orbit the Sun (or, in the case of a satellite, how does it orbit its parent planet)? Is the orbit nearly circular or is it highly elliptical? Is the orbit within the plane of the solar system or is the orbit highly tilted (inclined) with respect to the Earth's orbit around the Sun? Some orbits are very circular and not tilted (think Earth) and others are more elliptical and tilted (think Pluto).



ACTIVITY 15.1: VISUALIZING THE SCALE OF THE SOLAR SYSTEM

"Space is big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist's, but that's just peanuts to space."

— Douglas Adams, The Hitchhiker's Guide to the Galaxy

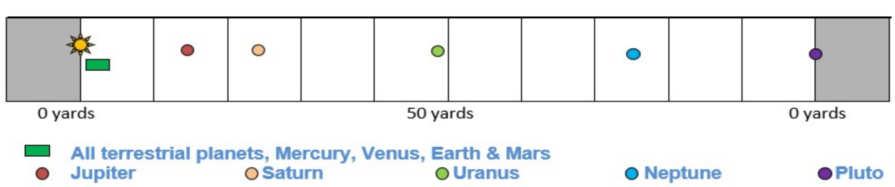
We will start our Solar System study by thinking a little bit about **the sizes of the planets and how far away they are from the Sun.** We going to use a website to help us build a table of the true distances and those distances converted to a scale where Pluto (actually a Kuiper Belt object, but it gets to be a planet again for this exercise) is 100 m from the Sun, or just farther than the length of a football field. Then we will go outside to recreate this!

Go to https://www.exploratorium.edu/ronh/solar_system/index.html. To create the solar system on a 100-meter scale, you need to enter a scaling factor for the size of the Sun that you want to use—in our case, 23.5 mm is how large the Sun is on this scale, or just smaller than one inch across. Then complete this table:

Object	*Size (km)*	*Scaled size (mm)*	*Distance from the Sun (km)*	*Scaled distance from the Sun (m)*
The Sun	1,391,900	23.5 mm	0 km	0 m
Mercury				
Venus				
Earth				
Mars				
Jupiter				
Saturn				
Uranus				
Neptune				
Pluto				100 m

Now let's go outside to see what this looks like!

Remember that we can't represent both the sizes and the distances to scale on one figure! But here is an approximate image of how far away everything is.



ACTIVITY 15.2: ANALYZING THE OBJECTS IN THE SOLAR SYSTEM

Let's start by placing some objects into bins immediately so that we can focus down on to the question of "what a planet is." Think about the main things that you know about planets. Think about what it means to you when someone asks you what a planet is.

1. What is the most basic thing that a given object in our solar system must do in order to be considered a planet?

2. Which objects in our solar system do NOT do this?

Now let's pull some solar system objects out of the running for planet status right away at the beginning so we can focus on those objects which primarily orbit the Sun.

STARS – this is our first category of objects within a solar system.

3. How many stars are in our solar system?

It turns out that having only one star in a given system is relatively rare. When you look up at night at the stars, about half of those stars are actually binary star systems with two stars orbiting each other. Some are triple- and even quadruple-star systems!! Imagine living in a different solar system where you have two, three or even four suns in the sky.

Above – Albireo, a double-star system in the constellation Cygnus.

Below – Alcor & Mizar, a quadruple star system in the constellation Ursa Major (the Big Dipper)

The mass of the Sun is 1.99×10^{30} kg.

The mass of all of the other objects in our solar system <u>combined</u> is 2.67×10^{27} kg.

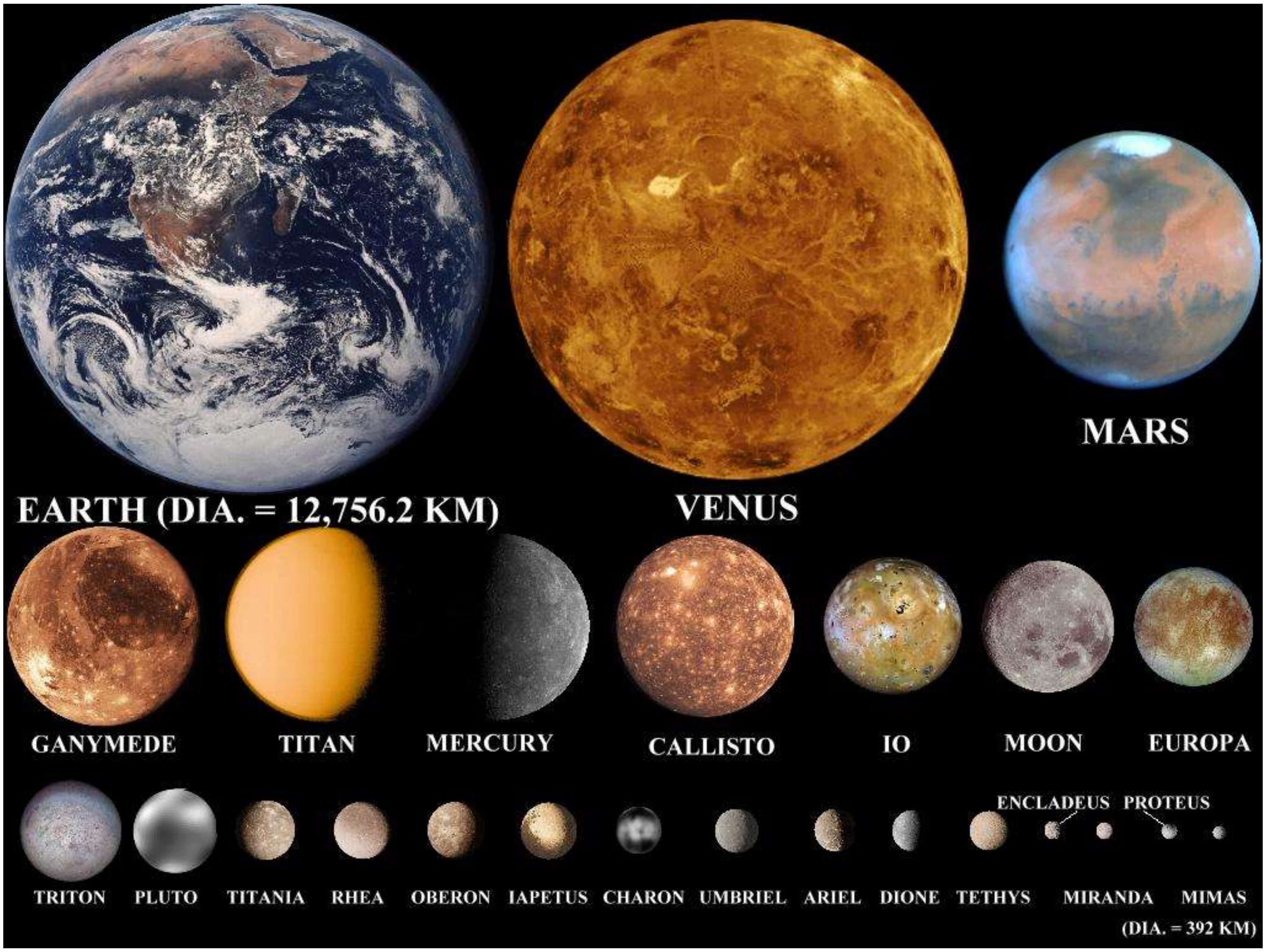
4. What percent of the mass of our ENTIRE solar system is contained within our star?

5. What are the basic properties of a star, or our Sun?

As we think about the solar system, as Earthlings, we often think that the Earth is a big deal, but the solar system is really all about the Sun. It is the vast Vast VAST majority of the mass of our solar system and really, the planets are just little dust bits orbiting around the Sun.

OK, so the Sun is a star and not a planet. Got it. Let's move on!

Next, let's remove the objects in our solar system that orbit around something *other than* the Sun. We're going to call these **SATELLITES.** The image below shows the largest satellites scaled to size with Earth, Venus, Mars, Mercury, and Pluto.



6. Can satellites be larger than planets?

7. How many satellites are larger than Pluto?

8. Can satellites be spherical?

9. If Ganymede or Titan were in orbit around the Sun, rather than Jupiter and Saturn (respectively), how would they be classified?

Now take a look at the data table below. Each row represents a different large object in our solar system that orbits the Sun. Column E tells you how many satellites each of the larger objects has.

10. Do all planets have satellites?

11. What is the basic definition of a satellite?

DATA TABLE – Lots of data about objects that orbit the Sun including their chemical compositions and orbital properties. We will come back to this chart and its color scheme throughout the rest of the lab.

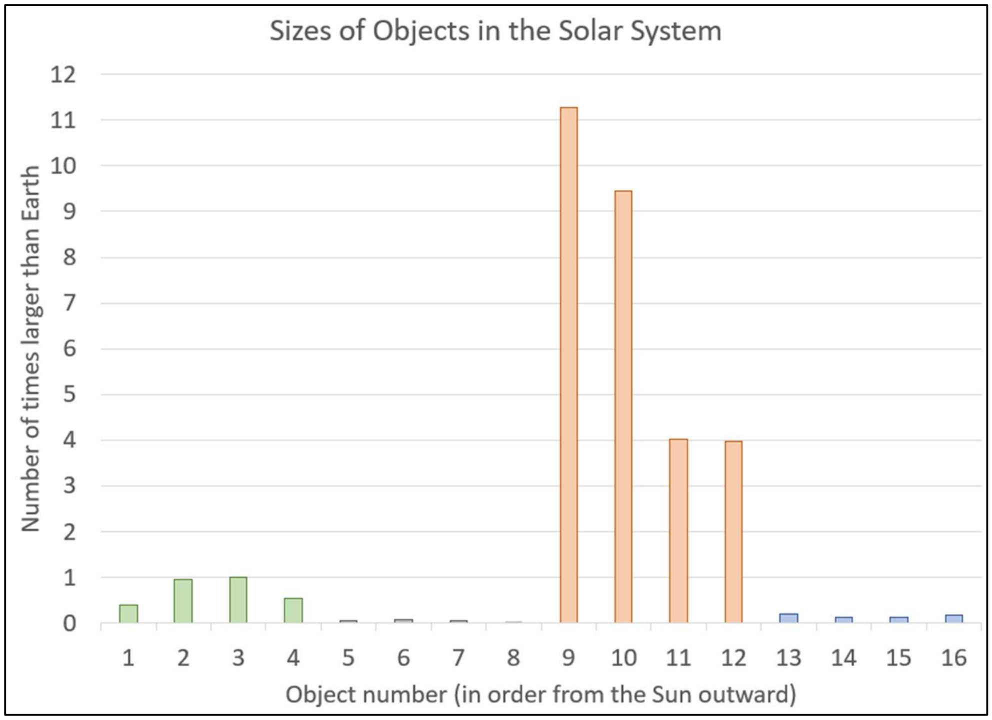
Stars	Terrestrial Planets	Asteroids	Jovian planets	Kuiper Belt Objects

A	B	C	D	E	F	G	H	I
Object Name	Semi-Major axis (AU)	Diameter (D_{earth})	Density (g/cm^3)	# Satellites	Rings ?	Orbital Period (years)	Orbital eccentricity (*e*)	Orbital inclination (degrees)
Sun	N/A	109	1.4	N/A	N/A	N/A	N/A	N/A
1 Mercury	0.39	0.38	5.4	0	No	0.24	0.205	7.0
2 Venus	0.72	0.95	5.2	0	No	0.62	0.007	3.4
3 Earth	1.00	1.00	5.5	1	No	1.00	0.017	0.0
4 Mars	1.52	0.53	3.9	2	No	1.88	0.094	1.9
5 Vesta	2.36	0.041	3.5	0	No	3.63	0.089	7.1
6 Ceres	2.77	0.074	2.2	0	No	4.61	0.076	10.6
7 Pallas	2.77	0.040	2.9	0	No	4.62	0.230	34.8
8 Hygiea	3.14	0.034	1.9	0	No	5.57	0.113	3.8
9 Jupiter	5.20	11.28	1.3	67	Yes	12	0.049	1.3
10 Saturn	9.54	9.45	0.7	62	Yes	30	0.057	2.5
11 Uranus	19.2	4.01	1.2	27	Yes	84	0.046	0.8
12 Neptune	30.1	3.96	1.7	14	Yes	165	0.011	1.8
13 Pluto	39.5	0.19	2.1	5	No	248	0.244	17.2
14 Haumea	43.2	0.12	2.0	2	Yes	284	0.195	28.2
15 Makemake	45.4	0.11	1.9	1	No	306	0.161	29.0
16 Eris	67.9	0.18	2.4	1	No	559	0.436	44.0

OK, now we are down to objects that are in orbit around the Sun. We could stop here and say that any object in orbit around the Sun is a planet. But let's see if we can classify these objects any further based on their chemical compositions and orbital properties.

Next let's look at **sizes of these objects**…

To the right is a plot of the sizes of the 16 different objects in the data table above in terms of their diameter or the number of times larger (or smaller) they are than the Earth. The x-axis is just the object number in order from closest to the Sun outward. The colors match the row colors in the table above and represent the groups into which planetary geologists put these objects.



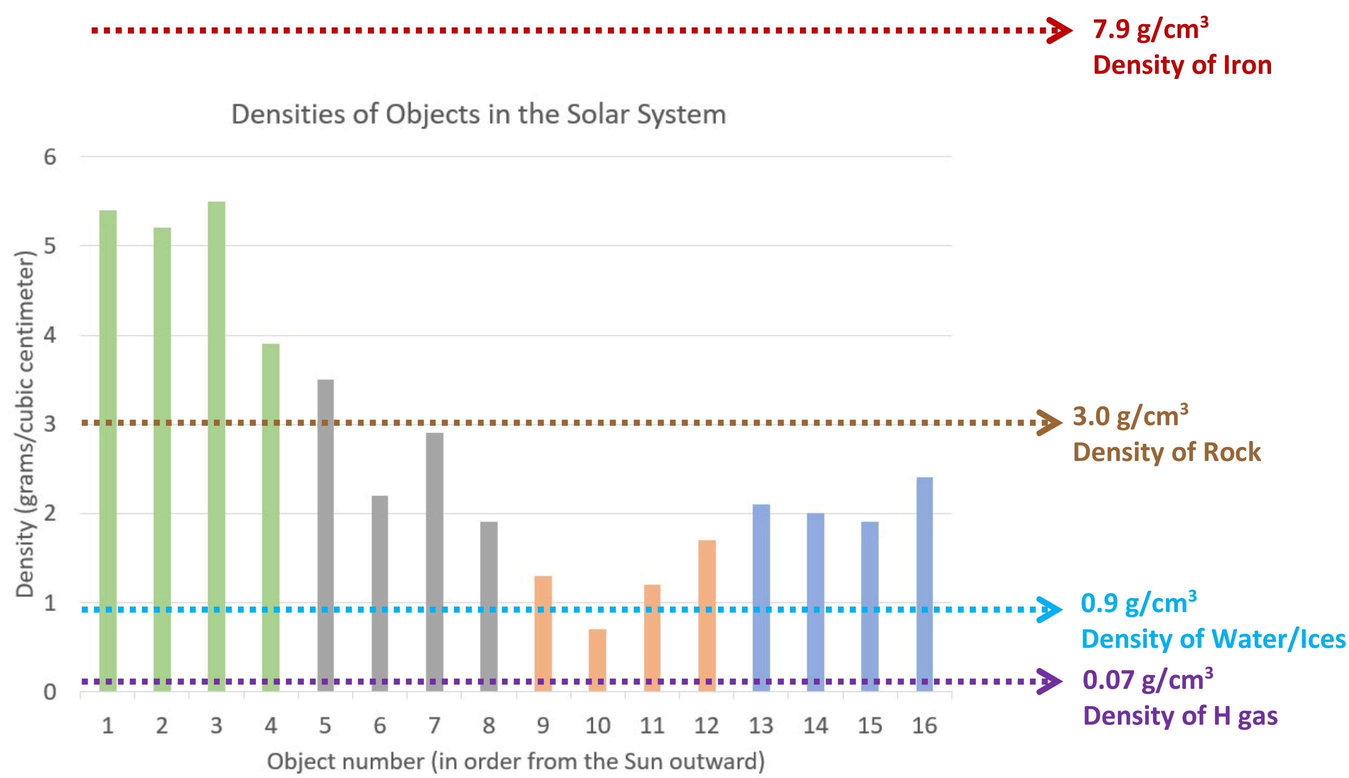
12. Which group of objects are the largest objects in the solar system (except for the Sun)?

13. Which group or groups of objects are the smallest?

Chemical Composition

The easiest way to get a quick idea of what a given planetary object (or any object, really) is made of is to look at its density. Recall that density is the amount of mass in a given object divided by its volume, or how large it is. Think about a tennis ball, which is mostly air, and how that feels lighter (or less dense) than a pool/billiard ball, which is solid. Imagine that you had a sphere of the same size made entirely out of iron—it would weigh approximately 2.6 pounds! Iron is a very dense element.

The materials available to create a solar system anywhere in the galaxy include **gasses** (mostly hydrogen and helium), **ices** (water, ammonia, and methane), **dust particles** (tiny rocks), and **metallic iron** (solid Fe). If we compare the densities of these solar system objects to the densities of these four main materials, we can get a rough idea of what the objects are made of. You can do that using the table above, but here is a graph!



The density of the planetary object is on the y-axis and given in grams/cubic centimeter (or g/cm^3). The densities of the common solar-system-forming materials are shown as well. In order to estimate what a given object is made of, you simply look at what types of materials you'd have to combine in order to get that object's density.

For example, let's choose the Earth. The Earth's average density is 5.5 g/cm^3 which lies between the densities of rock and iron. We would assume, therefore, that the Earth is primarily made up of rocks and iron metal and indeed, this is the case! About half of the radius of the Earth is all iron (the inner and outer core) while the outer half of the Earth is all rock. And so, Earth is a rocky-metallic body.

14. Which group of objects has the highest densities?

15. What two materials are these objects a mixture of?

16. Within this group of objects, which has the largest iron core?

17. Within this group of objects, which has the smallest iron core?

18. Which group of objects has the lowest densities?

19. Would any of these objects float on water? How do you know?

20. Using what you know about this group of objects, what are they PRIMARILY composed of?

21. Given the data in the graph above, is it likely that any of these objects have rocky cores? How do you know?

22. What two materials are the Asteroids and Kuiper Belt Objects made up of?

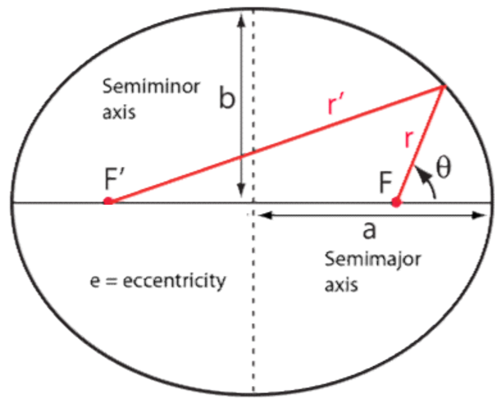
23. Which of these two groups has more rock than ice?

24. Which of these two groups has more ice than rock?

25. Is it possible that some of these smallest objects have metallic iron in them? Explain your response.

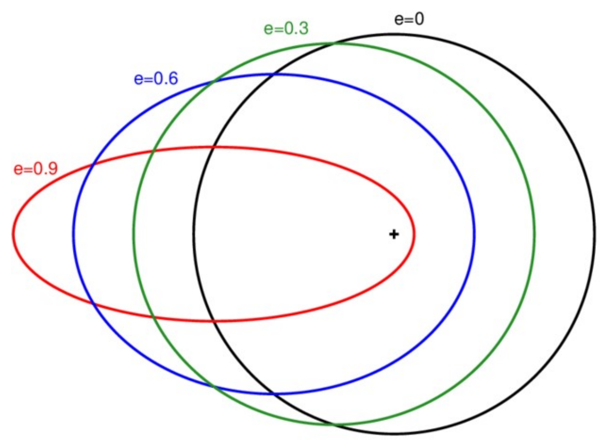
And so we generally talk about (1) high-density solar system objects that are mostly rock and metals, (2) low density objects that are mostly gaseous and icy, and (3) medium-density objects that are rocky and icy. However, recognize that the densities within these groups can vary widely based on what exactly each specific object is made of.

26. Match the category of objects with their general density.



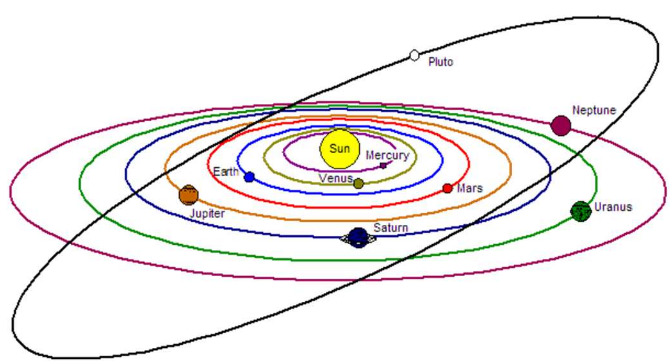
Next let's check out the **Orbital Properties** of these various objects. Recall that Kepler figured out his three laws of planetary motion that all objects in orbit around another object follow.

Kepler's First Law is that ***A Planet Moves on an Elliptical Orbit with the Sun at one Focus***. An ellipse is a squashed circle and the amount of "squashiness" or how elliptical the orbit is can be measured with the **eccentricity**, *e*. Recall that the *e* = 0 for a circle and approaches *e* = 1 for highly elliptical orbits, like that of a comet.

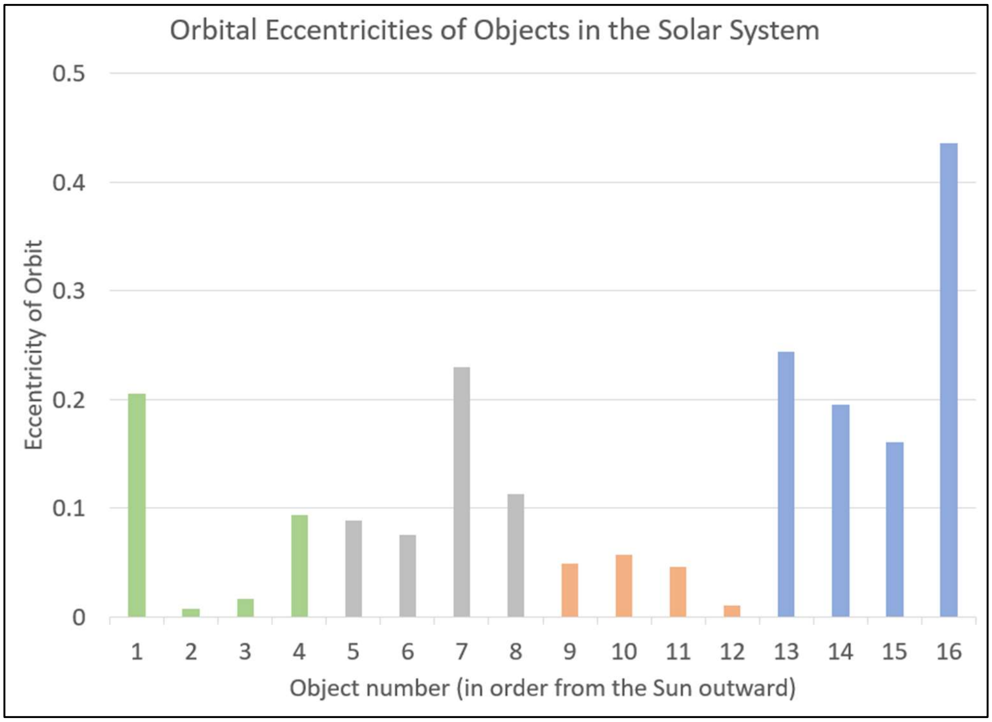


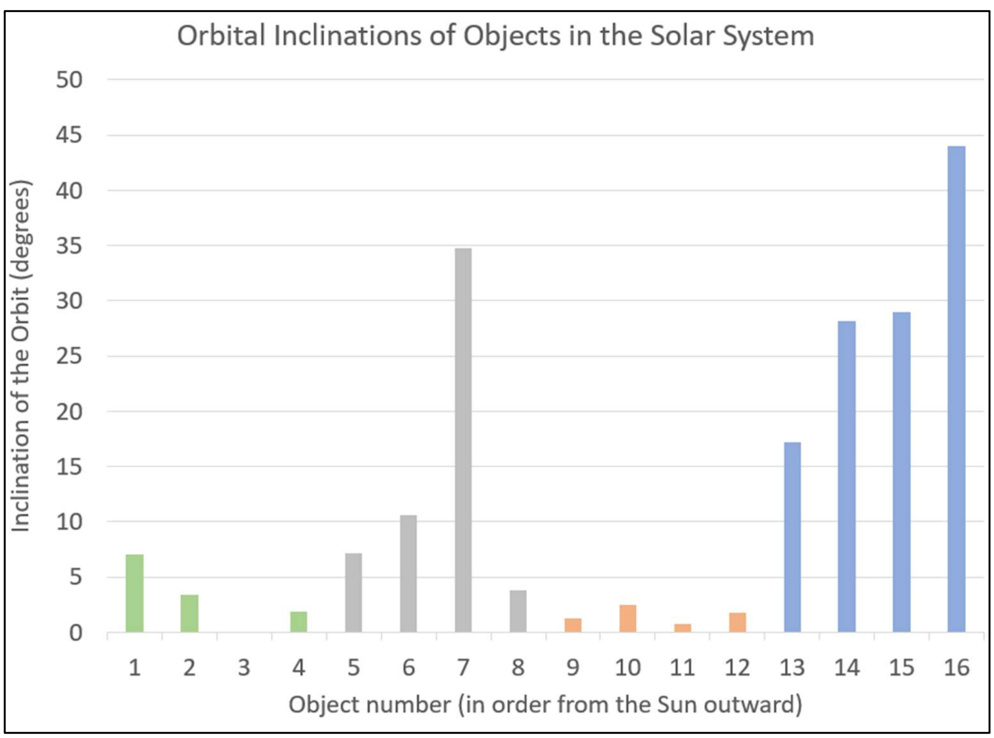
When we are looking down on the northern pole of the Earth and looking at how elliptical these orbits are, we are only seeing a two-dimensional picture of what a true orbit looks like around the Sun.

If we now look at the orbits from the side, or edge-on to the Earth's orbit around the Sun, we can see that some orbits are also tilted with respect to the Earth-Sun orbital plane and therefore different objects will travel above and below the plane of the solar system. The angle that the orbit is above or below the Earth-Sun orbital plane is called the **inclination of the orbit**. It can range from 0° to ±90° (which is straight up and down). Note that Pluto's orbit is very inclined to the plane of the solar system.



The two graphs below show you the orbital eccentricities and inclinations for these solar system objects. As planetary geologists, we look for “well-behaved” orbits vs. “less well-behaved” orbits. The BEST orbit would be one that is a perfect circle exactly aligned with the Earth’s orbit around the Sun. A much less well-behaved orbit would be highly elliptical and tilted with respect to the Earth’s orbit around the Sun.





27. Which TWO classes of objects have the most elliptical orbits on average?

28. Which TWO classes of objects are tilted the least to the plane of the solar system?

29. Of the Terrestrial Planets, which one is the least well-behaved?

30. Why is it harder for that planet to have a well-behaved orbit at its location in the solar system?

31. In general, characterize these different groups of objects based on their orbital properties.

Having looked at all of these data, how can you classify these four groups of objects when you combine what you know about their chemical compositions and their orbital properties.

32. Match these four groups of objects to the best description.

33. In which group does Pluto best fit?

34. What is it about Pluto that makes it not a good fit for either of the planet groups?

Now, for fun. . . . Go to https://www.exploratorium.edu/ronh/age/, enter your birthday and find out when your next birthdays are on the different planets in the solar system.

35. Which member of your group has a birthday on Jupiter next?

36. Which member of your group has a birthday on Mercury next?

NOTES

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Lab 16—Synthesis
Reflecting on Earth Science: Lecture and Lab

PART I: Mind mapping

Today we reflect upon our work in Physical Geology Laboratory this semester. Use this space to make a list of seven concepts or skills that you learned or became more confident in during this course.

1.

2.

3.

4.

5.

6.

7.

Now use the large paper, a pen or pencil, and any other art supplies you like. Use the seven concepts you listed above to build your mind map of this class. Refer to the examples provided (Figures 15.1 and 15.2) for suggestions on how you might structure your mind map. You may also want to visit a website such as http://www.mindmapinspiration.com/ for inspiration. You can lay it out however makes the most sense to you, in whatever way you visualize the skills, knowledge, and abilities you have acquired this semester.

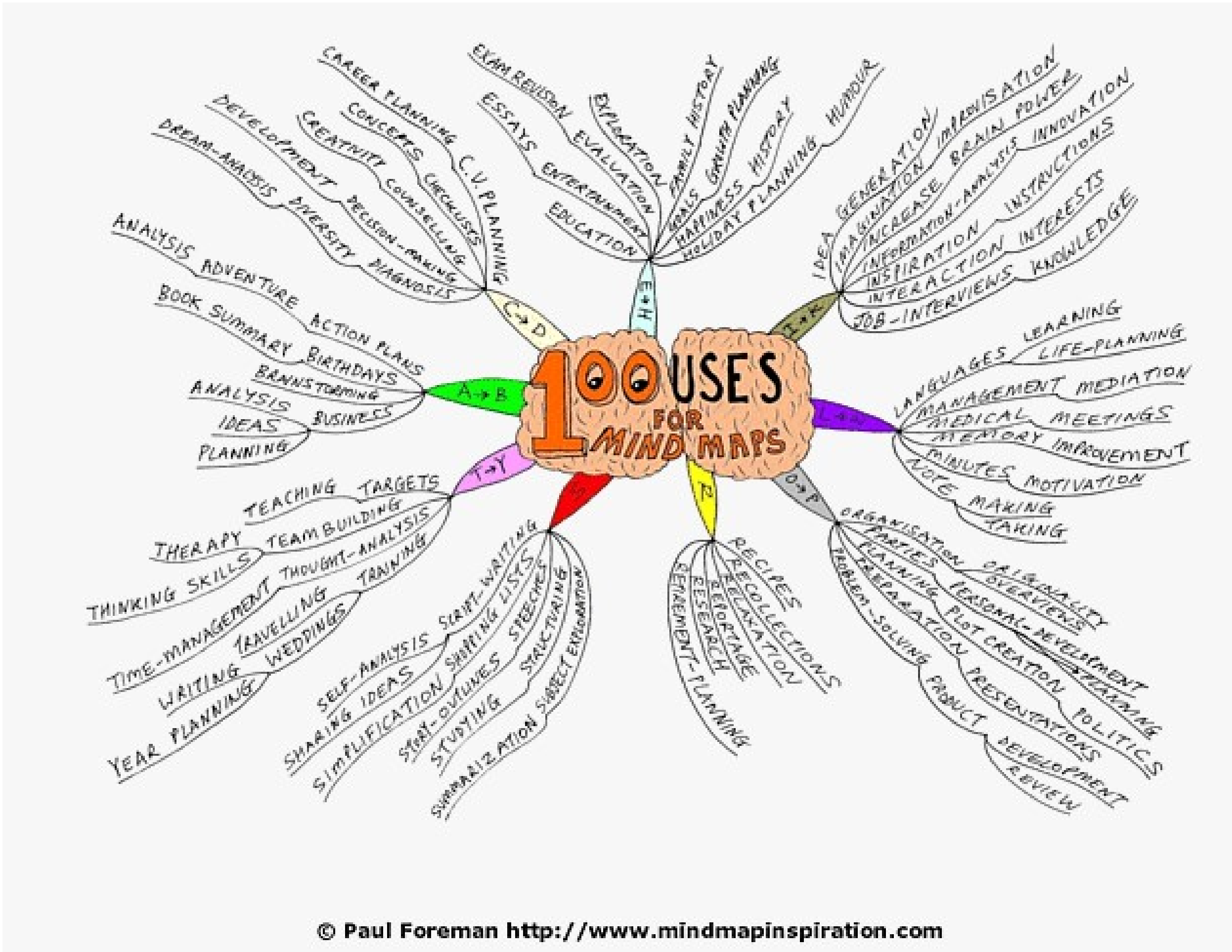

Figure 15.1. A mind map about mind mapping (Foreman, n.d.).

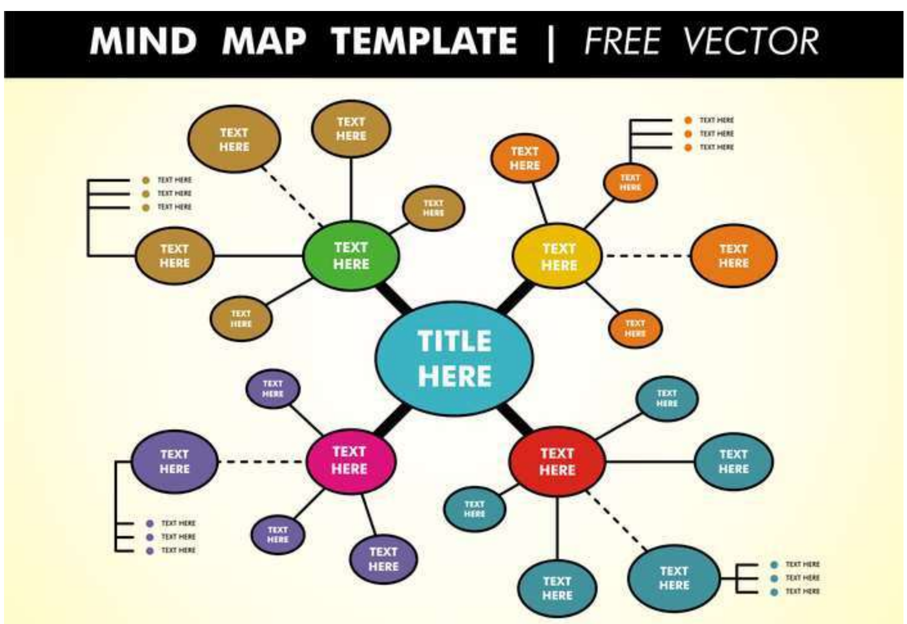

Figure 15.2. A basic mind map layout template (Vecteezy, 2019).

PART II: Looking forward

Review the mind map you made in Part I. Which three concepts are most important to you? Write a paragraph about each describing how you might apply that concept in future studies or professional work.

1.

2.

3.

NOTES

Extra credit 1—Take a hike! (adapted from Jefferson, 2008)

Assignment procedure

1. Go for a hike in an outdoor location or visit a local, state, or national park. While you are there, take some field notes about the geologic features and processes you see. Also make sure to get a photo, map, or brochure.
2. Write a one- to two-page descriptive essay about at least four earth science features or processes that you observed. You should make sure to use correct terms to identify the features and describe how you knew what you were looking at. Also make sure that your essay includes geographical information (trail, park, nearest city, state).
3. Here are some location ideas to get you started: Alexandria Community Park, Devou Park, Big Bone Lick State Historic Site, Boone Cliffs State Nature Preserve, Gunpowder Creek Nature Park, Mt. Airy Forest, Cincinnati Nature Center, Clifton Gorge State Nature Preserve, Glen Helen Nature Preserve, Red River Gorge Geological Area, Hocking Hills State Park, Serpent Mound, Ohio Caverns. There are so many great places nearby, so please don't feel limited to this list!
4. Submit your essay with your field notes, sketches, photos, park brochure or map here. Be sure to cite the authors when quoting or paraphrasing information, maps, or figures from external sources.

NOTES

Extra credit—Explore your hometown (adapted from Cochiara, 2008)

Assignment procedure

Research the geology of your hometown or any location that is special to you. Prepare a two-page paper plus one figure that illustrates a geological aspect of your study region. Include a list of references cited for your paper.

To find topographic and geologic maps of your location, search online at https://store.usgs.gov/maps, https://ngmdb.usgs.gov/topoview/viewer/#4/39.98/-100.06, or use your favorite topographic and geologic map smart device apps.

Topographic map: Examine the map, and record, at a minimum, the following information:

- map coverage (7.5-minute or 15-minute quadrangle?)
- map scale
- contour interval (with units)
- map publisher
- publication date of map (year)
- overall relief of the map (minimum and maximum elevations), with units
- the elevation of your house or point of interest, with units
- latitude and longitude coordinates of your hometown
- any other information that is interesting to you

Geologic map: Examine the map and record, at a minimum, the following information:

- map title
- map author(s)
- map publisher and publication date
- map scale
- geologic units in your hometown area. Be sure to include the unit names and ages. For example, “lower Cambrian sillimanite-mica schist” or “Paleozoic granite gneiss.”
- geologic structures in the region (faults, folds, domes, depressions, etc).
- overall strike and dip of units, if given. Example: “units generally strike N-S, with east facing dips of 35-80°”
- any other interesting information

Note: Your geologic map envelope may contain multiple maps (such as maps of bedrock geology, “surficial” geology, glacial geology, mineral deposits, zones/types of metamorphism, etc.) depending on the region, and may also contain a summary paper of the regional geology to go along with the maps. Feel free to use any extra information from these materials in your paper if you find it interesting. Be sure to cite the authors when quoting or paraphrasing information, maps, or figures from external sources.

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