# A Practical Guide to Introductory Geology

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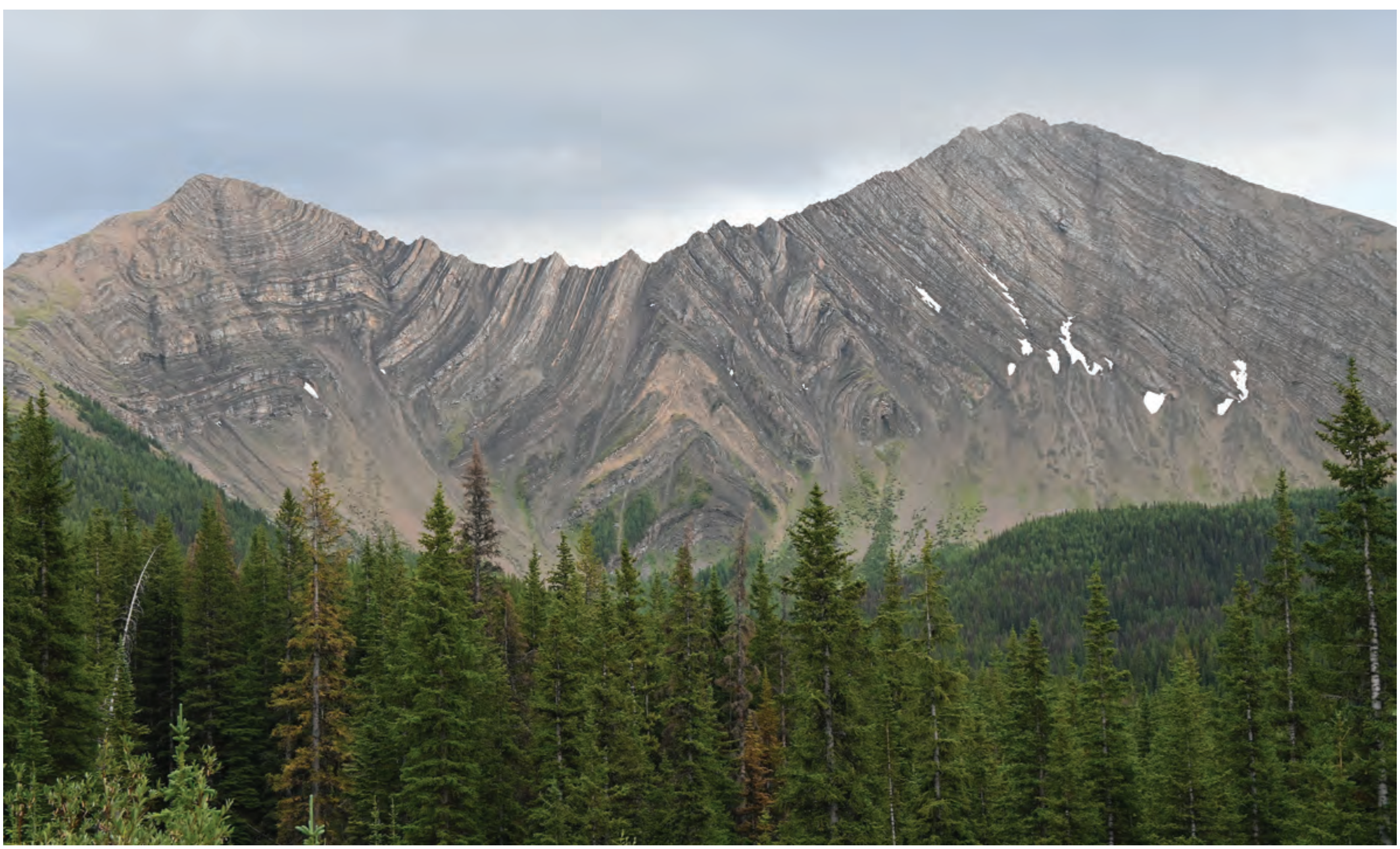

# GOOGLE EARTH TUTORIAL

## This is a pre-lab tutorial activity to be completed independently before Lab 1.

*Learning Objectives*

After completing the exercises in this tutorial assignment, you should understand how to use Google Earth Pro to:

- Examine the Earth's surface in plan view and in three-dimensions.
- Use the compass to understand direction when navigating in Google Earth Pro.
- Use the scale bar and measure tools to determine on-the-ground distances.
- Specify locations using geographic and Universal Transverse Mercator (UTM) grid systems.
- Modify the options in Google Earth Pro to use metric or imperial units, and geographic or UTM coordinates.
- Search for specific locations by place name or using geographic coordinates.
- View historical satellite imagery to examine changes to an area over time.

Google Earth Pro is an excellent tool for visualizing landscapes using satellite imagery. We will be using Google Earth Pro in several lab exercises in this course to examine volcanoes, rivers, and geologic structures. You will need to be familiar with how to navigate and use various features in Google Earth Pro to complete these exercises. To prepare for your first lab, complete the tutorial assignment in the next section before you meet for Lab 1.

If you are familiar with Google Earth Pro and the use of geographic and UTM coordinate systems to describe locations on Earth, this tutorial should take you about 25 minutes to complete. If you are not familiar with Google Earth Pro or the use of geographic and UTM coordinate systems, this tutorial could take up to 1 hour to complete. Contact your lab instructor if you have questions as you complete this tutorial.

To get started, download Google Earth Pro (free) for desktop: https://www.google.com/earth/versions/. Although there are also web and mobile versions of Google Earth Pro available, these do not have all the features you will be required to use in this course. It is recommended that you use the desktop version on a computer.

# Getting Started in Google Earth Pro

Once you have downloaded and installed Google Earth Pro for desktop, open the program on your computer.

In the search bar in the upper left part of your screen, type in "Mount Royal University". Click ***Search***.

You are now looking at a bird's eye view, or map view of the Mount Royal University (MRU) campus. This is definitely a bird's eye view: in the bottom right-hand* corner of the image it will tell you the altitude from which you are looking down. In Figure T1, we are looking down at MRU from an altitude of 2.12 km!

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*Note that these instructions have been written for Google Earth Pro on a PC running Windows 10. If you are using a Mac computer, the description of where certain features are found may differ. Contact your lab instructor for more information.

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*Text boxes like this one contain questions you need to answer, or specific actions you need to practice, in order to complete this tutorial assignment.*

From what altitude are you looking down on MRU?

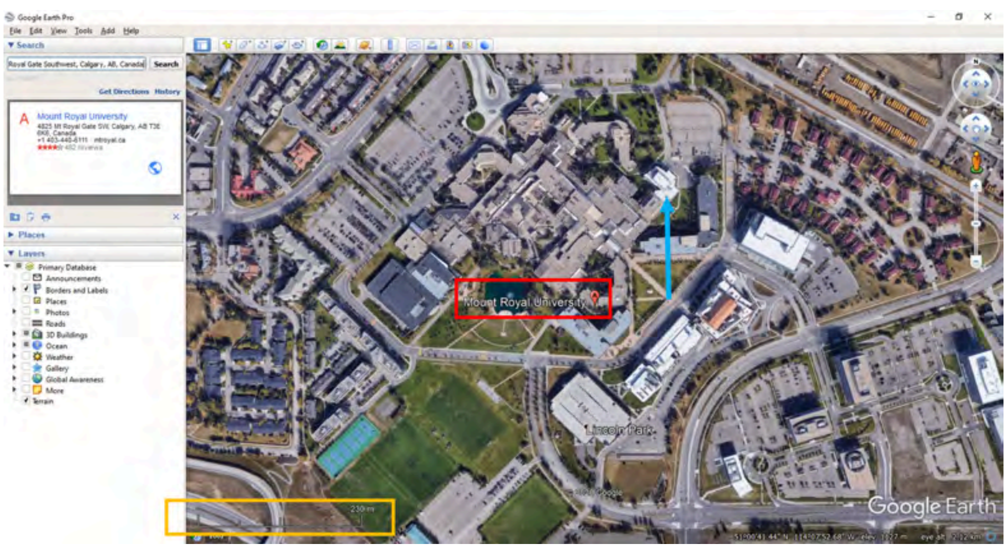


*Figure T1: Annotated Google Earth map view of Mount Royal University (MRU), highlighting where to find the location marker for MRU (red box), the scale bar (yellow box), and north (blue arrow and compass in upper right corner).*

Let's point out a few things you should know about Google Earth.

1. The red place marker shows the name and the exact location of the place you typed into the search bar. (See the red box in Figure T1 below)
2. In the top right corner, the compass shows which direction is north in the current view. In Figure T1, north is toward the top of the image (in the direction of the blue arrow).
3. The bar in the bottom left corner of the image shows the **scale bar** (inside the orange box in Figure T1). A scale bar helps you determine the actual, on the ground, distance between points or along lines. In

Figure T1 below, the entire length of the scale bar represents a real distance of 230 m, and each division along the scale bar represents a real distance of 57.5 m.

Try spinning the view around by clicking on the ‘N’ on the compass, holding down your mouse, and spinning the ‘N’ around. You can also hold down the shift key and use the right and left arrow keys on your keyboard to rotate the view.

To return to the original view press the letter ‘r’ on your keyboard, or click ***View, Reset, Compass***.

Let’s check out a few more features in Google Earth. Look at the numbers in the bottom right corner of the image (See red box in Figure T2).

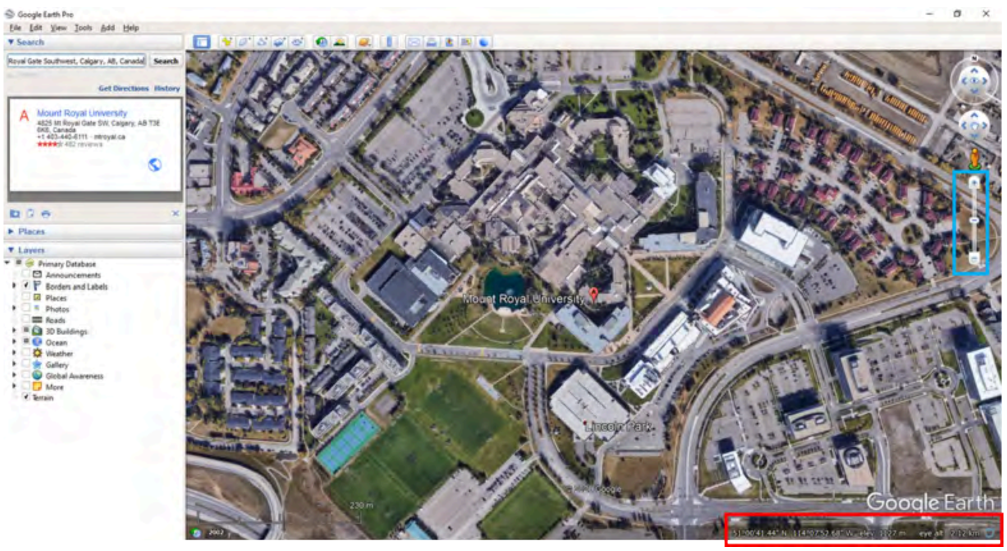


*Figure T2: Annotated Google Earth map view of MRU highlighting the location information shown in the red box. In this example, the location of the cursor is given in latitude and longitude coordinates. The information in this area of the screen also shows the elevation of the land at the location specified by the cursor, which is 1127 m above sea level in this example.*

What happens to these numbers as you move your cursor around?

These numbers are the **coordinates** for the cursor location and they change as you change the position of the cursor. Coordinates are used to specify an exact location using a series of numbers in a **grid system.** Grid systems are used to divide the Earth’s surface into imaginary squares formed by two sets of perpendicular lines. Two common grid systems used in Google Earth that we will use throughout this term are **geographic** (latitude and longitude), and**Universal Transverse Mercator**(UTM). We will come back to the concept of grid systems in the next part of this tutorial.

The sliding bar in the blue box in Figure T2 can be used to zoom in and out. You can also zoom in and out using the scroll wheel on your mouse or the keyboard shortcuts defined in the table below. Notice how when you do this, the number value on the scale bar changes. Zooming in and out changes the scale of the image.

What happens when you zoom in dramatically? You probably jump into “Street View” (See Figure T3). To return to map view, click on "Exit Street View" in the top right corner.


*Figure T3: An example of street view in Google Earth. To exit Street View, click on "Exit Street View" in the top right-hand corner of the image.*

Now let's explore how we can measure distances in Google Earth. First, make sure you are back in map view. To do this, on your keyboard press 'r', or click ***View, Reset, Tilt and Compass.***

Click on the ruler icon in the toolbar located at the top of the screen. A dialogue box should pop up (see Figure T4). Let's use a line to measure the length of the two soccer fields at MRU. Click once to start measuring and click again to stop. What distance did you measure? In Figure T4, the length of the line measured represents a real distance of 151.47 m.

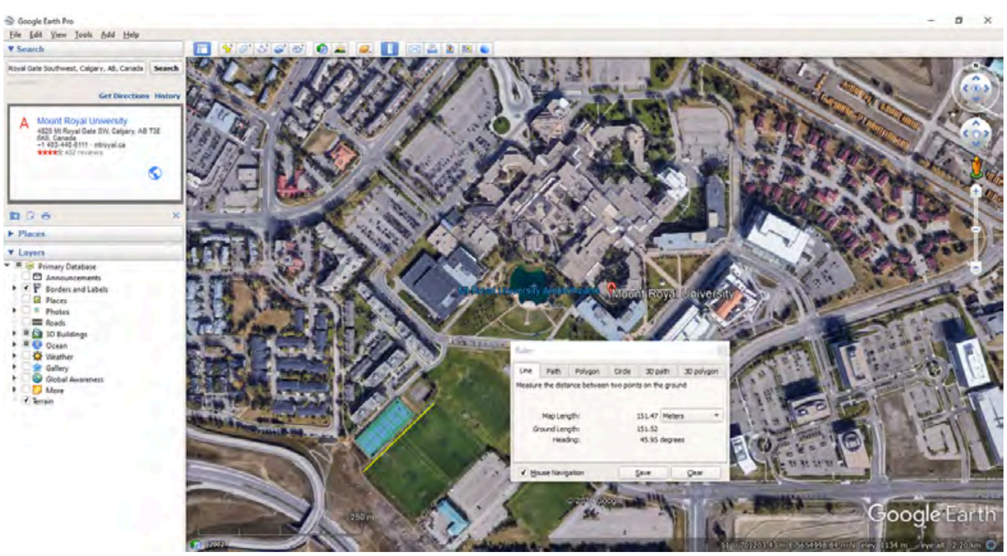


*Figure T4: Using the ruler tool to measure distances in Google Earth. The dialogue box will tell you the length of the line you are measuring. This example shows that the length of two soccer fields at MRU is 151.47 m (see yellow line on map).*

You can also measure the length of a path, rather than just a straight line. Figure T5 shows a measured path along the ring road around MRU. The total length of the path is 1.55 km. Notice that you can change the unit of measurement by using the drop down menu. Click ***clear*** to erase the line or path you measured.

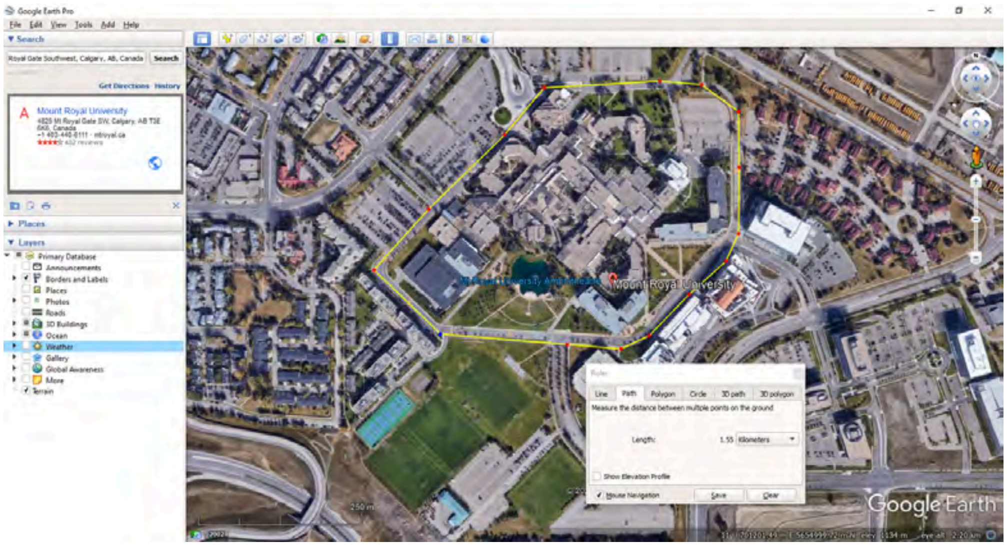


*Figure T5: Using the ruler tool to measure the length of a path, rather than a simple straight line. The length of a path drawn around the ring road of MRU is 1.55 km (see yellow path on image).*

Let's try changing some options in Google Earth Pro. Click on ***Tools, Options.*** The dialogue box shown in Figure T6 should appear. Examine the ***3D View*** tab, where you can choose between using UTM coordinates or Lat/Long coordinates (Figure T6, red box). Choose to display lat/long coordinates in one of three ways: decimal degrees, degrees-minutes-seconds, or degrees-decimal minutes. You can also change the default units of measurement (Figure T6, blue box) from imperial (feet, miles) to metric (metres, kilometres). When you are happy with your selections, click ***Apply.***

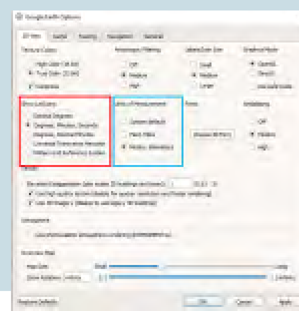

*Figure T6: Annotated options menu in Google Earth highlighting where grid coordinates (red box) and units of measurement (blue box) can be changed.*

Finally, let's examine some historical satellite imagery. Google Earth is a great tool for examining changes to Earth's surface over the past few decades. By clicking on the clock icon in the top toolbar (Figure T7, red arrow), you can see historical imagery for the area on your screen. Use the scroll bar to look through the historical imagery of the city of Calgary from an altitude of ~70 -80 km.

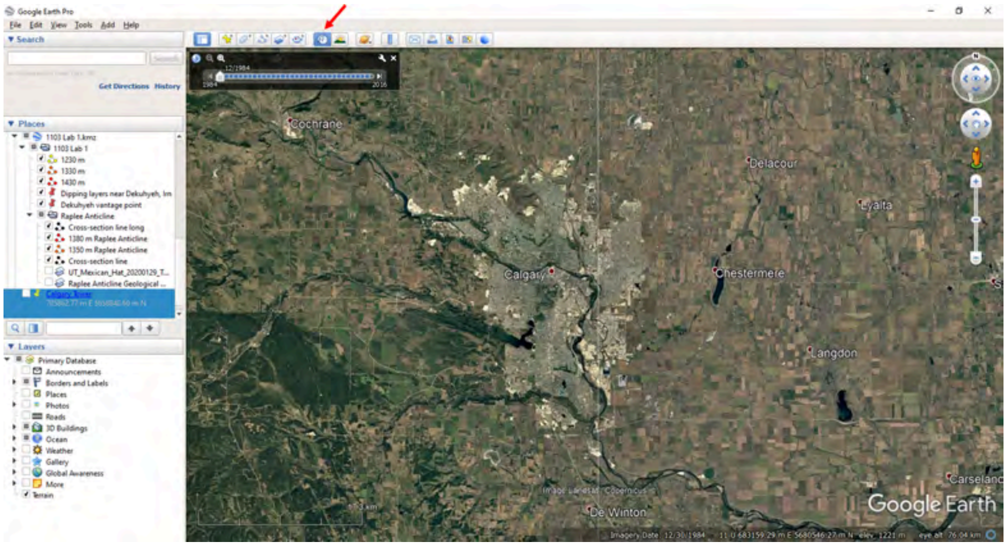

*Figure T7: Annotated historical Google Earth imagery of Calgary and surrounding areas from 1984.*

What distance is represented by the entire length of the scale bar?

In what year was the oldest image of this area at this scale captured?

In what year was the most recent image of this area at this scale captured?

## Keyboard Shortcuts for Google Earth Pro

| **Action** | **Shortcut (Windows & Linux)** | **Shortcut (Mac)** |
|---|---|---|
| Move left | Left arrow | Left arrow |
| Move right | Right arrow | Right arrow |
| Move up | Up arrow | Up arrow |
| Move down | Down arrow | Down arrow |
| Rotate clockwise | Shift + Left arrow | Shift + Left arrow |
| Rotate counter-clockwise | Shift + Right arrow | Shift + Right arrow |
| Tilt up | Shift then click and drag down | Shift + Down arrow |
| Tilt down | Shift + Up arrow<br>Shift then click and drag up | Shift + Up arrow |
| Reset to north-up view | n | n |
| Reset to top-down tilt | u | u |
| Return to plan and north-up view | r | r |
| Zoom in | + | + |
| Zoom out | – | – |
| Stop current motion | Spacebar | Spacebar |

## Media Attributions

- Figures T1, T2, T3, T4, T5, T6, T7 used under the following Google Maps and Google Earth guidelines.

# Grid Systems and Coordinates

## What is a grid system?

A grid is a regular pattern made of squares formed by two sets of lines that intersect at right angles. Grid systems are used to precisely identify locations on a map. The two types of grid systems we will cover in this course are:

- **Geographic**, where locations are specified using degrees and minutes of **latitude** and **longitude.**
- **Universal Transverse Mercator (UTM),** where locations are specified in metres using an **easting** and **northing.**

Depending on your settings in Google Earth Pro, you might be using the geographic grid system (latitude and longitude) OR the Universal Transverse Mercator grid system (UTM). If you are not sure which grid system you are using, return to the Options menu to check.

### Latitude and longitude

The geographic grid system is made up of **meridians of longitude** and **parallels of latitude**. Figures T8 and T9 illustrate the geographic grid system in Canada.

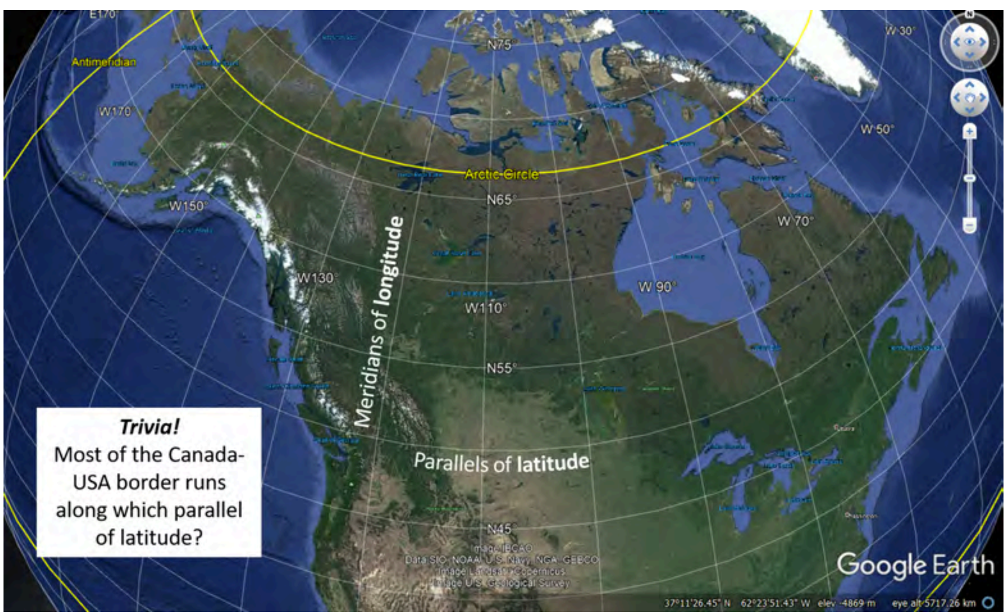


*Figure T8: The geographic grid system is comprised of meridians of longitude and parallels of latitude. Meridians of longitude run north-south whereas parallels of latitude run east-west.*

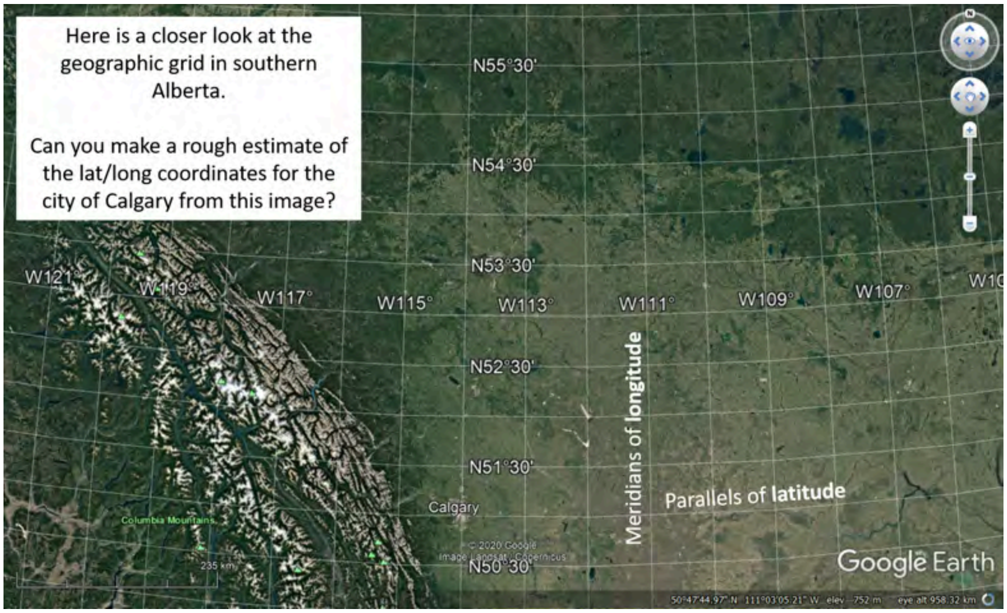

*Figure T9: Geographic grid system displayed over southern Alberta.*

Coordinates that describe an exact location on the surface of Earth are represented in degrees, minutes and seconds of latitude and longitude. Depending on the accuracy required in locating a point on a map, **degrees** (°) may be subdivided into 60 subdivisions known as **minutes** (‘) and minutes may be subdivided into 60 subdivisions known as **seconds** (“). The line of 0° longitude is the **prime meridian** located in Greenwich, England, and longitude increases from 0° to 180° as you move east or west away from the prime meridian. The line of 0° latitude is the **equator**, and latitude increases from 0° to 90° as you move north or south towards the poles.

When using the geographic grid system, one must specify whether coordinates are north (N) or south (S) of the equator, and east (E) or west (W) of the prime meridian. For anywhere in Canada, latitude will always be north of the equator and longitude will always be west of the prime meridian, e.g., 51°02’39” **N** 114°03’47” **W.** Notice that latitude is listed first, followed by longitude. Together, these coordinates describe an exact location.

Try typing these coordinates into the search bar in Google Earth. What geographic feature is located at 51°02’39” N 114°03’47” W? See Appendix 2 for Google Earth Tutorial answers.

## Universal Transverse Mercator (UTM)

In this grid system designed by the military, Earth’s surface is divided into 60 north-south zones designated by a number and letter, each covering 6° of longitude in width (Figure T10). Inside each zone, coordinates are measured in metres north and east. The city of Calgary is actually divided into two UTM zones: zone 11 U and zone 12 U (Figure T11).

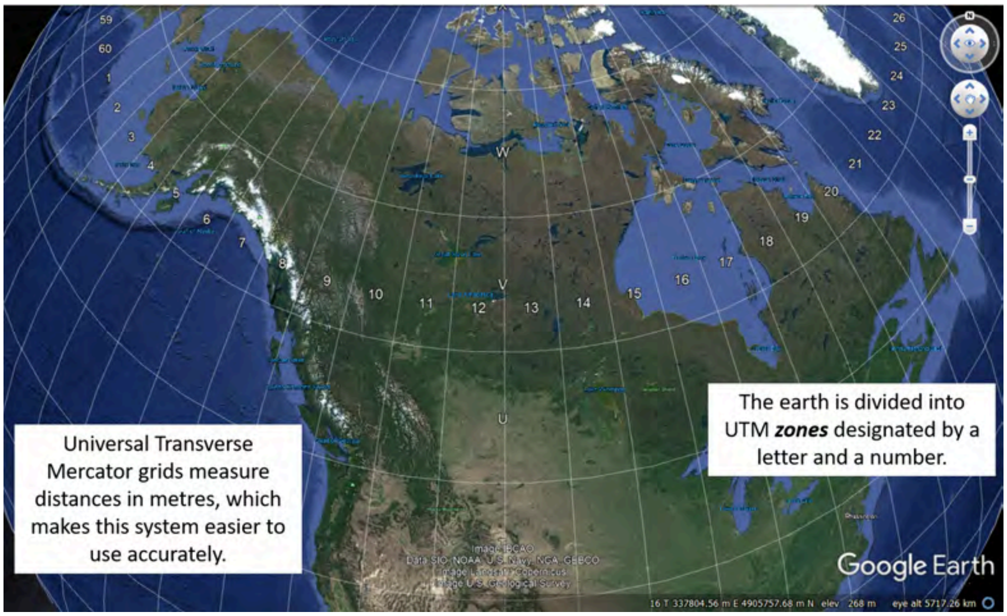


*Figure T10: Universal Transverse Mercator (UTM) zones in Canada. Zones are designated by a number and a letter, e.g., the city of Vancouver, BC is in UTM zone 10 U.*

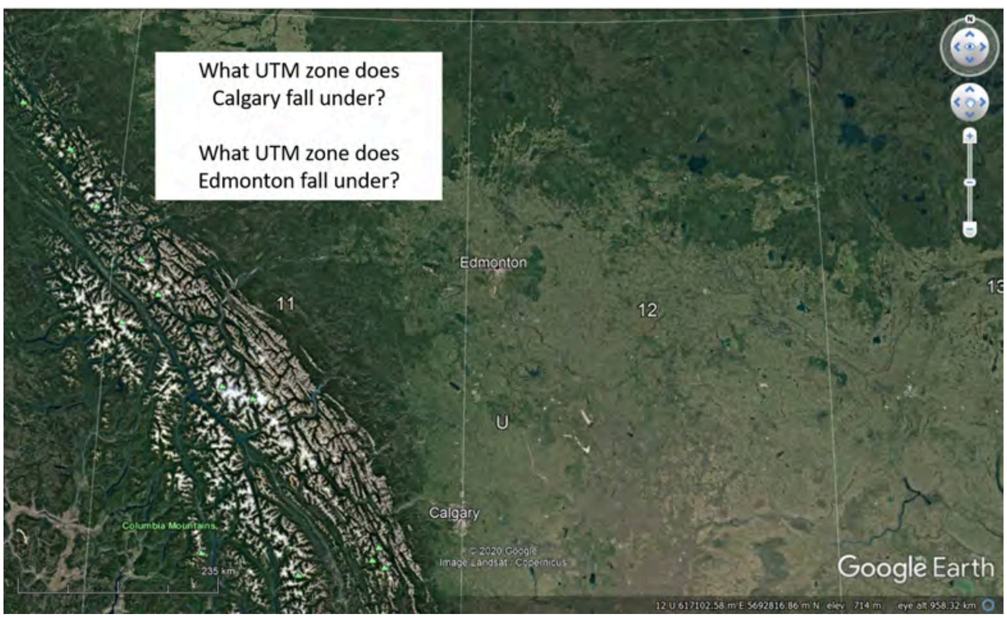


*Figure T11: Universal Transverse Mercator (UTM) zones 11 U and 12 U in Alberta.*

A UTM coordinate always begins with the zone, which in the case for most of Calgary is 11 U. The **easting** is always given first, followed by the **northing**. For example, 11 U 705863 m E 5658841 m N are the approximate coordinates for the Calgary Tower.

In Figure T12, a point is located using UTM coordinates 11 U 708400 m E 5659200 m N, meaning that the location is known to within a 100 m by 100 m square. If you were using GPS to pin-point your location, you might be able to record UTM coordinates to within a 1 m by 1 m square, and your coordinates might look something like: 11 U 708411 m E 5659284 m N. Note that the UTM system is a true metric measuring system, and that it is the easiest to use accurately.

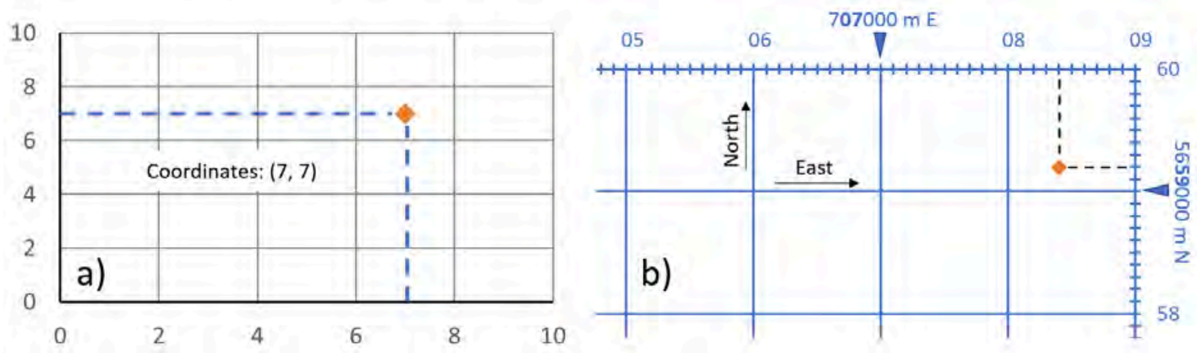

*Figure T12: An example of coordinates (7, 7) plotted on a simple X-Y graph (a, left) and the same principle used to plot a point using UTM coordinates for zone 11 U in Calgary (b, right). Notice how not all the numbers labeled along the edge are written in full. Some values are abbreviated to save space on the map, e.g., the number 06 represents the grid line for easting 706000 m E, and the number 58 represents the grid line for northing 5658000 m N.*

## Universal Transverse Mercator (UTM) grid references

Instead of reporting the full UTM coordinates, an abbreviated 6-digit **grid reference** can be reported to give a location to nearest 100 m. To report an abbreviated grid reference, look at the nearest grid line and estimate tenths of a square eastward or northward from this line to the location of interest. Record the UTM zone followed by the three digits in the 10000, 1000 and 100 position for both the easting and the northing.

For example, the full UTM coordinates **<u>11 U</u>** 7**<u>084</u>**11 m E 56**<u>592</u>**84 m N can be abbreviated using only the bolded and underlined portions of the full coordinates, **<u>11 U 084592.</u>**

### *Using grid coordinates to find a location*

Using coordinates to specify a position in a grid is just like locating a point on a simple X-Y graph. On an X-Y graph, the first number in the coordinate refers to the position along the X-axis and the second number refers to the position along the Y-axis (Figure T12 a). To use coordinates in a geographic grid system, simply use the labeled grid lines or graticules around the outer border of a map and plot the longitude first, followed by the latitude. To use coordinates in a UTM grid system, simply use the labeled grid lines or graticules around the outer border of a map and plot the easting first, followed by the northing (Figure T12 b).

*Your turn to practice finding and describing locations using grid coordinates*

1. What are the UTM coordinates (easting and northing) of the point in Figure T12 b?
2. Try plotting the coordinate 11 U 707500 m E 5658200 m N on Figure T12 b.
3. In the UTM grid shown in Figure T12 b, what is the length in metres of each side of each square on the grid?
4. To see the grid lines for each system in Google Earth, click on ***View, Grid***. Try zooming in and out to see how each grid type looks. Try this using the geographic grid (lat/long) and the UTM grid.
5. Type “Mount Royal University” into the search bar and click ***Search***. Hover your cursor right on the place

marker. What are the coordinates for MRU in lat/long? Remember, you must specify that MRU is north of the equator and west of the prime meridian!

6. What are the coordinates for MRU in UTM coordinates? Remember, you must specify the zone number!
7. What are the coordinates for MRU in UTM as a grid reference? Remember, you must specify the zone number!

See Appendix 2 for Google Earth Tutorial answers.

## Media Attributions

- Figures T8, T9, T10, T11 used under the following Google Maps and Google Earth guidelines.
- Figure T12: © Siobhan McGoldrick. CC BY.

# LAB 1: PLATE TECTONICS

## Lab Structure

| | |
|---|---|
| Recommended additional work | Yes – complete Google Earth Tutorial before Lab 1 |
| Required materials | Pencil, pencil crayons, ruler, printed Plate Boundaries Map |

*Learning Objectives*

After carefully reading this section, completing the exercises within it, and answering the questions at the end, you should be able to:

- Explain the difference between oceanic and continental crust.
- Describe the motion of plates at divergent, convergent, and transform boundaries.
- Characterize divergent, convergent, and transform plate boundaries by their associated geological features and processes.
- Describe how mantle plumes and resulting hot spot volcanoes can be used to determine the direction of plate motion.
- Understand the historical contributions of geoscientists who proposed the theory of plate tectonics.

## Key Terms

- Lithosphere
- Continental crust
- Oceanic crust
- Mantle
- Asthenosphere
- Tectonic plate
- Divergent
- Convergent
- Transform
- Seismology
- Volcanology
- Bathymetry
- Topography
- Geochronology
- Mantle plume
- Hot spot

# Lab 1 Exercises

## Activity I: Plate Boundary Characteristics

In this activity you will learn to identify types of plate boundaries based on the characteristics they exhibit. This activity is based on the "Discovering Plate Boundaries" activity by Dale S. Sawyer at Rice University and modified based on teaching experiences at the SEOS department of the University of Victoria, Canada.

In groups, we will examine five types of plate boundaries today:

- Ocean-Ocean **Divergent** (the boundary between two plates where oceanic crust is being pullled apart)
- Ocean-Ocean **Convergent** (where two plates of oceanic crust are moving toward one another leading to the subduction of one plate)
- Ocean-Continent Convergent (where oceanic and continental crust are moving toward one another leading to the subduction of the oceanic crust)
- Continent-Continent Convergent (where two plates of continental crust are moving toward one another)
- Ocean-Ocean **Transform** (where oceanic crust is moving horizontally in opposite directions across a transform fault)

To start, download or view the plate boundaries map. Seven plate boundaries are highlighted and numbered on your map. You will also be assigned a map displaying one of four data sets: volcanoes, earthquakes, topography/bathymetry, and seafloor age.

You will each, individually, study your data set and attempt to draw conclusions about what geological features and processes characterize each of the numbered plate boundaries.

Later in lab today, you will be joining a live video conference in small groups to share your observations with your group mates. You will be asked to summarize your observations so write down your conclusions and be prepared to teach your peers!

### Step 1

Examine your assigned map. Start by locating all the numbered plate boundaries on your assigned map. Are they easy or difficult to find? Looking closely at your data type, start making notes about the ***spatial distribution*** of the data points. Exactly what you look for will vary with data type. For the point data (volcanoes and earthquakes) you are looking for ***distribution patterns***. For surface data (topography and seafloor age) you are looking for where the surface is high and where it is low, where it is old and where it is young. In this activity you are focusing on ***observations, not interpretations,*** meaning that you do not need to worry about why there is or is not a pattern, you just need to observe and record what you see. You are analyzing the data, not interpreting them!

## Step 2

Now focus your attention on the numbered plate boundaries on the plate boundaries map. Identify the nature of your data near each of the numbered plate boundaries. Is it high or low, symmetric or asymmetric, missing or not missing, varying along the boundary or constant along the boundary, etc. Complete Table 1.1 below to classify the plate boundaries based on your observations of your assigned data, using the tips below for guidance. Right now, you will only fill in the column for your assigned data set. Remember: do not try to explain the data; just observe!

Below are some suggestions for the kinds of observations that are useful for each data set. Compare your boundary to the types of boundaries on the map as you do this. Remember, the goal is to find unique characteristics for each boundary type.

**Volcanoes:** Observe and make notes on the distribution patterns. Are the volcanoes near a given boundary randomly distributed, tightly clustered, or do they define a linear trend?

**Earthquakes:** Observe and make notes on the distribution patterns and depth of the earthquakes. Note both the range of depths (extremes) and the more typical or average. For example, a given boundary might have all shallow earthquakes (0- 33 km) with rare deeper earthquakes between 33 -70 km depth. Earthquakes might be randomly distributed, tightly clustered, or may define a linear trend.

**Topography/bathymetry:** Look for any topographic features that seem to be related to the boundary, such as nearby mountain chains, deep sea trenches, broad gradual highs or lows, offset (broken and shifted) features, etc. Briefly describe how extreme they are (e.g., a very high or wide mountain chain). Make sure that you understand how the colour scale on the map represents elevations above sea level. For example, your should recognize that bright fuchsia colours correspond to large negative values and represent the deepest parts of ocean where the seafloor is far beneath sea level.

**Seafloor age:** This data set can be tricky; be careful not to see patterns where there are none! For example, you might observe that in some places, the seafloor age changes from place to place along the boundary. In this case there is no clear pattern and this indicates no relationship between seafloor age and the boundary, but this is still a good observation! Alternately, the seafloor age may be the same everywhere along the boundary, or it may change in a consistent pattern. Do your best to describe what you see, and whether or not your observations fit a clear, consistent pattern.

# PLATE BOUNDARY MAP

This map is from Dietmar Mueller, Univ. of Sydney

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

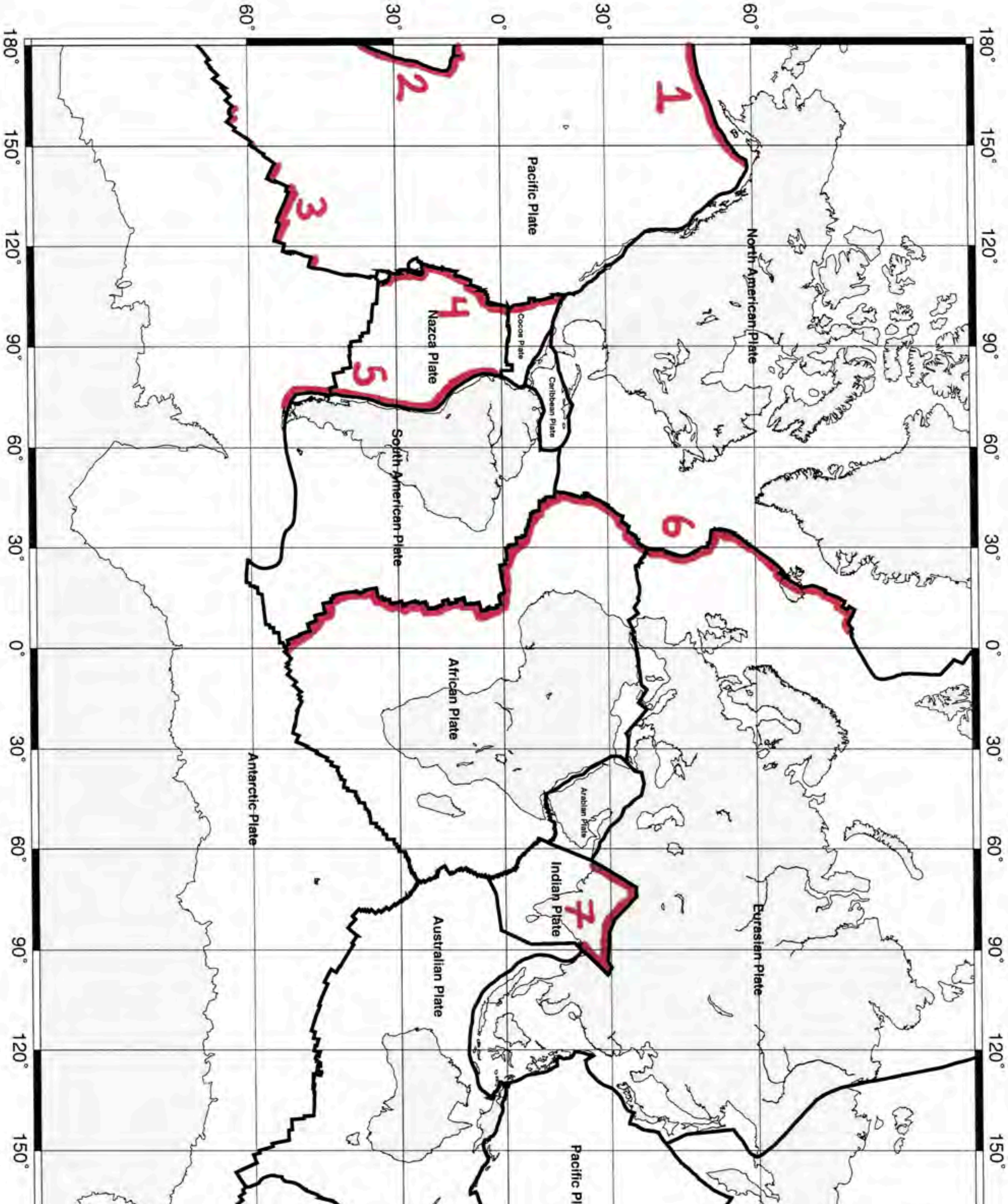

**Table 1.1: Summarize the key features from each data set that characterize each type of plate boundary in this table.**

| Boundary Type | Volcanism | Earthquake Activity | Bathymetry/Topography | Seafloor Age |
|---|---|---|---|---|
| **Ocean-Ocean Convergent**<br><br>**(#1 and #2)** | | | | |
| **Ocean-Ocean Transform**<br><br>**(#3)** | | | | |
| **Ocean-Ocean Divergent**<br><br>**(#4 and #6)** | | | | |
| **Ocean-Continent Convergent**<br><br>**(#5)** | | | | |
| **Continent-Continent Convergent**<br><br>**(#7)** | | | | |

## Step 3

Everyone has been randomly assigned to a group and provided with a link to a video meeting to discuss your observations in real time in groups of four. Each group has at least one representative of each data set. Consider yourselves a group of experts gathering to compare observations. In your group, introduce yourself and what type of data you have been analyzing. Taking turns, each group member will share their observations about their assigned data set from Step 2. It is helpful to share your screen while you teach, so that your group members can see your data. If you are not sure how to share your screen, ask your instructor. Your instructor will periodically join each group video meeting group to check in while you complete this part of the activity.

Work together in your group to complete Table 1.1 by summarizing your observations on the characteristics of each type of plate boundary. By the end of this activity, each member of your group should have a completed Table 1.1. Each group member should be able to describe the characteristics of each type of plate boundary using all four data types.

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# Activity II: Hot Spot Volcanoes and Plate Motion

In this activity you will use data from chains of hot spot volcanoes in Google Earth Pro to make a rough estimate of the rate of motion of the Pacific Plate, and to determine the direction of plate motion for several different tectonic plates. This activity and the Google Earth data provided are based on the "Determining Plate Rates From Hot Spot Tracks Using Google Earth" activity developed by Susan Schwartz and Erin Todd at the University of California-Santa Cruz.

## Step 1

Download the Hawaii-Emperor.kmz file provided by your instructor to examine hot spot volcanoes in Google Earth Pro. Load the file into Google Earth Pro by double-clicking on the file, or in Google Earth Pro by clicking on ***File, Open*** and navigating to where you saved the .kmz file.

## Step 2

Once the Hawaii-Emperor.kmz is loaded, click and drag to move it from "Temporary Places" to "My Places." Then save "My Places" by clicking ***File, Save, Save My Places***. This .kmz file will now be available every time you open Google Earth Pro on this computer. ****NOTE:** When you close the program, Google Earth Pro should save everything in "My Places", but to be safe you should manually save "My Places" to your computer whenever you make significant changes to it.

## Step 3

Examine the data in the Hawaii-Emperor.kmz file to answer the questions below. Each place marker indicates a location where a volcanic rock was sampled and dated. This type of dating uses radioactive elements in the rock to give geologists a precise age of when the lava cooled and solidified to form a volcanic rock. The number next to each place marker is the age of the rock in millions of years (Ma). The current location of the hot spot at Kilauea Volcano in southeast Hawai'i is shown by the marker labeled 0 Ma.

### *Hot Spot Volcanoes and Plate Motion Exercise Questions*

1. Using what you learned in the Google Earth Tutorial, list the lat/long coordinates of Kilauea Volcano, Diakakuji Seamount (located at the bend in the Hawaii-Emperor chain), and Midway Island.

2. Using what you learned in the Google Earth Tutorial, list the UTM coordinates of Mauna Kea (located near the centre of the island of Hawai'i), the 75.82 Ma volcano near Detroit Seamount (located near the northern end of the Hawaii-Emperor chain), and the 5.77 Ma volcano on Kaua'i. Remember to include the zone at the beginning of the coordinate!

3. Using the ruler tool in Google Earth Pro, found in the top toolbar, measure the distance between the present location of the hot spot at Kilauea Volcano and Midway Island in kilometers (km). Measure the distance as a line from the point of each pin and round to the nearest whole km.

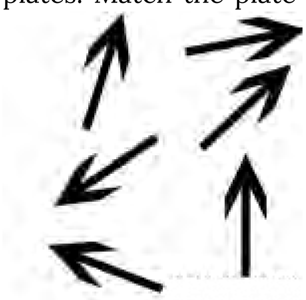
4. Make a rough estimate of the average rate of motion for the Pacific Plate in kilometres per million years. To do this, divide the distance between two volcanoes along the chain by their difference in ages (shown in millions of years, Ma). The rate is calculated as the distance over time. Round to the nearest tenth.

5. Most plate rates reported in scientific literature are measured in cm/yr. Convert your estimated rate to cm/yr. Again, round your result to the nearest tenth. Remember this calculation is a rough estimate!

6. Examine the entire length of the Hawaii-Emperor chain. What do you think might have caused this chain to form such a distinctive “elbow-like” shape?

Download the HotspotVolcanism.kmz file provided by your instructor and load it into Google Earth Pro. Remember to save it in “My Places” once it is loaded into Google Earth Pro! Notice that this file includes the locations of boundaries between tectonic plates as well as place markers and ages for volcanoes along several hot spot chains (or tracks) around the world.

7. Based on the hot spot tracks shown in the HotspotVolcanism.kmz file and the ages of the volcanoes, determine the direction of plate motion for the African, Australian, Nazca, North American, and Pacific plates. Match the plate name to the arrow that most closely illustrates the vector (direction) of motion.



8. Predict whether the plate boundary between the following pairs of plates is *convergent* or *divergent* based on the plate motion determined from the hot spot tracks:

a) Pacific & Nazca Plates

b) South American & African Plates

See Appendix 3 for answers to lab exercises.

## Media Attributions

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# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 1.1 Discovering Plate Tectonics | Giant strides were made in understanding Earth during the middle decades of the 20th century, including discovering magnetic evidence of continental drift, mapping the topography of the ocean floor, describing the depth relationships of earthquakes along ocean trenches, measuring heat flow differences in various parts of the ocean floor, and mapping magnetic reversals on the sea floor. By the mid-1960s, the fundamentals of the theory of plate tectonics were in place. |
| 1.2 Plates, Plate Motions, and Plate Boundaries | Earth's lithosphere is made up of over 20 plates that are moving in different directions at rates of between 1 cm/y and 10 cm/y. The three types of plate boundaries are divergent (plates moving apart and new crust forming), convergent (plates moving together and one being subducted), and transform (plates moving side by side). Divergent boundaries form where existing plates are rifted apart, and it is hypothesized that this is caused by a series of mantle plumes. Subduction zones are assumed to form where accumulation of sediment at a passive margin leads to separation of oceanic and continental lithosphere. Supercontinents form and break up through these processes. |
| Lab 1 Exercises | Characteristic features of divergent, convergent, and transform plate boundaries can be explored by examining global datasets of volcanology, seismology (earthquakes), topography/bathymetry, and seafloor age displayed on a world map. Since tectonic plates move over a mantle plume that we assume to be stationary, we can use chains or tracks of hot spot volcanoes to interpret the direction of plate motion. By using the age of these hot spot volcanoes, and the distance between volcanoes in the same chain, we can estimate the rate of plate motion. |

# LAB 2: MINERAL PROPERTIES AND NON-SILICATE MINERALS

## Lab Structure

| | |
|---|---|
| Recommended additional work | Yes – review concepts from Labs 1 and 2 in preparation for Test 1 |
| Required materials | Mineral ID kit, Mineral Kits 1 and 2, pencil |

*Learning Objectives*

After reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Describe mineral lattices and explain how they influence mineral properties.
- Categorize minerals into groups based on their compositions.
- Describe some of the important techniques for identifying minerals.
- Identify and describe the physical properties of a range of non-silicate minerals in hand sample.
- Discuss the economic uses of non-silicate minerals.

## Key Terms

- Cation
- Anion
- Silicate
- Non-silicate
- Native element
- Sulphide
- Oxide
- Hydroxide
- Sulphate
- Carbonate
- Halide
- Phosphate
- Colour
- Streak
- Lustre
- Hardness
- Crystal habit
- Cleavage
- Fracture
- Conchoidal fracture
- Specific gravity

Minerals are all around us: the graphite in your pencil, the salt on your table, the plaster on your walls, and the trace amounts of gold in your computer. Minerals can be found in a wide variety of consumer products including paper, medicine, processed foods, cosmetics, electronic devices, and many more. And of course, everything made of metal is also derived from minerals.

As defined in the introductory chapter, a mineral is a naturally occurring combination of specific elements arranged in a particular repeating three-dimensional structure (Figure I4).

"***Naturally occurring***" implies that minerals are not artificially made. Many minerals (e.g., diamond) can be made in laboratories, but if they can also occur naturally, they still qualify as minerals. "***Specific elements***" means that most minerals have a specific chemical formula or composition. The mineral pyrite, for example, is $FeS_2$ (two atoms of sulfur for each atom of iron), and any significant departure from that would make it a different mineral. But many minerals can have variable compositions within a specific range. The mineral olivine, for example, can range all the way from $Fe_2SiO_4$ to $FeMgSiO_4$ to $Mg_2SiO_4$. Intervening compositions are written as $(Fe,Mg)_2SiO_4$ meaning that Fe and Mg can be present in any proportion, and that there are two of them for each Si present. This type of substitution is known as **solid solution**.

Most important of all, a mineral has a specific "***repeating three-dimensional structure***" or "lattice," which is the way in which the atoms are arranged. We've already seen in Figure I4 of the introductory chapter how sodium and chlorine atoms in halite alternate in a regular pattern. Halite happens to have the simplest mineral lattice, most other minerals have more complex lattices. Some substances that we think must be minerals are not because they lack that repeating 3-dimensional structure of atoms. Volcanic glass is an example, as is pearl or opal.

# Lab 2 Exercises

The exercises below will guide you through the mineral samples in Mineral Kits 1 and 2. Review the physical properties of minerals presented in Chapter 2.3 before you begin these exercises. You may wish to consult the mineral identification tables at the back of this manual as you complete the exercises below.

## Part I: Cleavage and Fracture

The minerals in this part include a mix of silicate and non-silicate minerals found in Mineral Kits 1 and 2.

1. Do the following samples exhibit cleavage or fracture? If the sample exhibits cleavage, specify the number of cleavage planes and approximate angle between them.

| **Sample** | **M226S** | **M225S** | **M1S** | **M251S** | **M111S** | **M223S** | **M131S** |
|---|---|---|---|---|---|---|---|
| **Cleavage or fracture** | | | | | | | |

2. What is the difference between a crystal face and a cleavage plane?

3. Look at sample M202(S). This is a good example of a mineral with 2 cleavages at almost right angles to each other. Select two other samples that also demonstrate this type of cleavage.

4. Now select a sample which also appears to have a least two cleavages but with the cleavage surfaces oblique (at some angle other than 90°) to each other.

5. Which sample has one (perfect) cleavage only?

6. Look at the fractured surface of sample M225. Try to describe this surface (rough? curved? splintery? etc.). This is an example of **conchoidal fracture**. Does this sample exhibit any cleavage?

7. What other sample also exhibits conchoidal fracture?

---

## Part II: Non-silicate Minerals

Certain physical properties are diagnostic for a particular mineral. These diagnostic properties will help you distinguish a particular mineral. The questions below will help you identify these diagnostic properties. Remember: you must be able to identify all the physical properties of each mineral, not just the diagnostic properties. You should also know the group to which each mineral belongs (e.g., sulphides, oxides).

### *Mineral Group: Native Elements*

| **Sample M21** | **Mineral name:** |
|---|---|

1. Does this mineral exhibit cleavage? ________If yes, describe the cleavage: ______________________
2. What is the approximate hardness of the sample on the Mohs scale of hardness? _________
3. What is the specific gravity of the sample (high, medium or low)?

---

4. Describe the lustre of this mineral: ____________________________________________
5. Describe the streak: ____________________________________________
6. What is a diagnostic property of graphite?

---

### *Mineral Group: Oxides*

| | |
|---|---|
| **Sample M11/M12** | **Mineral name:** |
| **Sample M51/M52** | **Mineral name:** |
| **Sample M53** | **Mineral name:** |

1. Do any of these samples exhibit cleavage? _________
2. If yes, which one? Describe the cleavage: ______________________
3. Looking at samples M51/52 and M53, what is the lustre of each sample?

| | |
|---|---|
| **Sample M51/M52** | **Lustre:** |
| **Sample M53** | **Lustre:** |

4. Compare the streak of each sample. Describe what you see:

---

5. Do any of the samples attract a magnet? Which one? ______________________
6. What is the diagnostic property of magnetite?

---

7. What is the diagnostic property of hematite?

---

### *Mineral Group: Carbonates*

| **Sample M251** | **Mineral name:** |
|---|---|

1. Does this mineral exhibit cleavage? __________ If so, describe the cleavage: ______________________
2. What is the approximate hardness of the sample on the Mohs scale of hardness? __________
3. Describe the lustre of this mineral.

---

4. Does the sample react to a drop of HCl? ________
5. What is a diagnostic property of calcite?

---

### *Mineral Group: Sulphides*

| | |
|---|---|
| **Sample M41/M42** | **Mineral name:** |
| **Sample M31** | **Mineral name:** |
| **Sample M1** | **Mineral name:** |
| **Sample M141** | **Mineral name:** |

1. What do all these minerals have in common?

---

2. Test all four minerals for hardness. Do any of these minerals scratch the glass plate? ____________________
_________________________

3. Which is harder pyrite or chalcopyrite? ___________________________________________
4. Describe the streak of sphalerite:

---

5. What is the lustre of pyrite, chalcopyrite and galena? ___________________________________________
6. What is the lustre of sphalerite? ___________________________________________
7. Which mineral has the highest specific gravity? ___________________________________________
8. Do you see cleavage faces on any of these minerals? ___________________________________________
9. How can you tell pyrite from chalcopyrite?

---

10. What is a diagnostic property of galena?

---

11. What is a diagnostic property of sphalerite?

---

12. Many sulphide minerals contain valuable ore metals that are used to manufacture the objects and technology you use every day. Using Appendix 4 as a guide, complete the table below.

| **Sample #** | **Mineral Name** | **Mineral Formula** | **Ore Metal** |
|---|---|---|---|
| **M1** | | | |
| **M31** | | | |
| **M141** | | | |

13. Name two economic uses for the mineral galena.

---

14. Explain the steps involved in extracting galena from an ore deposit and eventually producing pure lead metal.

---

---

## *Mineral Group: Sulphates*

| **Sample M241** | **Mineral name:** |
|---|---|

1. What is the approximate hardness of this mineral? ______________________
2. Describe the lustre of this mineral: _____________________________________________
3. What is the diagnostic property of gypsum?

---

4. What is the main economic use for gypsum and where is the world's most productive gypsum mining area?

---

## *Mineral Group: Halides*

| | |
|---|---|
| **Sample M231** | **Mineral name:** |
| **Sample M261** | **Mineral name:** |
| **Sample M262** | **Mineral name:** |

1. Describe the cleavage of each sample.

| | |
|---|---|
| **Sample M231** | **Cleavage:** |
| **Sample M261** | **Cleavage:** |
| **Sample M262** | **Cleavage:** |

2. What is the approximate hardness of the two minerals on the Mohs scale of hardness?

| | |
|---|---|
| **Halite:** | **Fluorite:** |

3. Compare the specific gravity of the two minerals. Which is higher? ______________________
4. What is a diagnostic property of halite?

---

5. What is a diagnostic property of fluorite?

---

6. How can you distinguish fluorite from quartz? Quartz is a silicate mineral that will be studied in Lab 3.

---

# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 2.1 Bonding and Lattices | The main types of bonding in minerals are ionic bonding (electrons transferred) and covalent bonding (electrons shared). Some minerals have metallic bonding or other forms of weak bonding. Minerals form in specific three-dimensional lattices, and the nature of the lattices and the type of bonding within them have important implications for mineral properties. |
| 2.2 Mineral Groups | Minerals are grouped according to the anion part of their formula, with some common types being oxides, sulphides, sulphates, halides, carbonates, phosphates, silicates, and native minerals. |
| 2.3 Mineral Properties | Some of the important properties for mineral identification include hardness, cleavage/fracture, density, lustre, colour, and streak colour.  It's critical to be able to recognize these properties in order to be able to identify minerals. |
| 2.4 Economic Minerals | Geological resources are critical to our way of life and important to the Canadian economy. Gold, coal, iron, copper, nickel, and potash are Canada's most valuable mined commodities. The concentrations of metals in mineral deposits are typically several thousand times higher than those in average rocks, and such concentrations only form through specific geological processes. Mining involves both surface and underground methods, but in either case, rock is brought to surface that can react with water and oxygen to produce acid rock drainage and metal contamination. |
| Lab 2 Exercises | The best way to learn mineral identification is to practice by examining the mineral samples in your Mineral Kit 1 and 2. It is important to know all the properties of each mineral in your kits, but especially the diagnostic properties that are most helpful for identifying each mineral. Remember, different samples of the same mineral may not always look exactly the same, but their other physical properties (e.g., hardness, cleavage, lustre) will be consistent. |

# LAB 3: SILICATE MINERALS

## Lab Structure

| | |
|---|---|
| Recommended additional work | Yes – review concepts from Labs 1, 2 and 3 in preparation for Test 1 |
| Required materials | Mineral ID kit, Mineral Kits 1 and 2, pencil |

*Learning Objectives*

After carefully reading this section, completing the exercises within it, and answering the questions at the end, you should be able to:

- Describe a silica tetrahedron and the ways in which tetrahedra combine to make silicate minerals.
- Differentiate between ferromagnesian and other silicate minerals.
- Identify and describe the physical properties of a range of silicate minerals in hand sample, and how these properties are used to identify minerals.

## Key Terms

- Isolated silicate
- Single chain silicate
- Double chain silicate
- Phyllosilicate (sheet silicate)
- Framework silicate
- Colour
- Streak
- Lustre
- Hardness
- Crystal habit
- Cleavage
- Fracture
- Conchoidal fracture
- Specific gravity

# Lab 3 Exercises

The exercises below will guide you through the silicate mineral samples in Mineral Kits 1 and 2. Review the physical properties of minerals presented in Chapter 2.3 before you begin these exercises. You may wish to consult the mineral identification tables at the back of this manual as you complete the exercises below. Note that all **silicate** minerals have **non-metallic lustre**. As you are observing the following samples keep in mind you have to classify the lustre using more descriptive terms such as vitreous, earthy or dull, pearly, satiny, etc. Remember: you must be able to identify all the physical properties of each mineral, not just the diagnostic properties.

## Silicate Mineral Group: Framework Silicates

1. Examine samples M221, M223, and M225. All of these samples are varieties of the same mineral. Name the mineral: ______________________
2. Describe the cleavage or fracture exhibited in these samples: ________________________________________
3. How can you distinguish between a cleavage plane and a crystal face?

---

---

4. Test all four minerals for hardness. What is the hardness of quartz? ___________
5. Describe the lustre of the samples. ____________________________________________
6. What is a diagnostic property of quartz?

---

7. Sample M225 is flint, an example of microcrystalline quartz that is always grey to black in colour. Do the diagnostic properties for quartz apply to flint as well?

---

### *Feldspars*

| | |
|---|---|
| **Sample M201** | **Mineral name:** |
| **Sample M202** | **Mineral name:** |
| **Sample M211** | **Mineral name:** |

You have a pink/salmon coloured sample and a white sample of **potassium feldspar (K-feldspar)**. A pink feldspar will always be K-feldspar, and may show **exsolution lamellae**. A white feldspar may be K-feldspar or plagioclase feldspar (**albite**). If you have a white K-feldspar and a white plagioclase feldspar look for **stria-**

**tions** on the plagioclase feldspar and that will differentiate them. The dark plagioclase feldspar (labradorite) will exhibit striations and has diagnostic iridescence.

1. Examine all your K-feldspar and plagioclase feldspars. These minerals are all **feldspars** however, we will refer to them by their mineral names and classify them as framework silicates. Test each sample for hardness:

| | |
|---|---|
| **Sample M201** | **Hardness:** |
| **Sample M202** | **Hardness:** |
| **Sample M211** | **Hardness:** |

2. Describe the cleavage exhibited by these samples: ___________________________________________

3. Looking at M201 and M211, do either of these samples exhibit striations? Do either of the samples exhibit iridescence?

4. How can you distinguish between K-feldspar and plagioclase feldspar?

## Silicate Mineral Group: Sheet Silicates (phyllosilicates)

| | |
|---|---|
| **Sample M121** | **Mineral name:** |
| **Sample M271** | **Mineral name:** |

1. Describe the cleavage of these two minerals: ___________________________________________
2. What is the hardness of these two minerals? ___________________________________________
3. What is a diagnostic property of mica minerals? ___________________________________________
4. How can you distinguish between muscovite and biotite?

| | |
|---|---|
| **Sample M281** | **Mineral name:** |

5. What is the hardness of the sample? ______________________
6. Describe the lustre of this mineral: ___________________________________________
7. What is a diagnostic property of talc?

| | |
|---|---|
| **Sample M291** | **Mineral name:** |

8. Describe the lustre of this mineral: ____________________________________________
9. What is a diagnostic property of kaolinite?

## Silicate Mineral Group: Single Chain Silicates

Single chain silicates include the **pyroxene** family of minerals. There is one pyroxene (augite) in the mineral kit and the samples vary in colour.

| **Sample M101** | **Mineral name:** |
|---|---|

1. Describe the cleavage of the pyroxene: ______________________
2. What is the colour of this mineral? ______________________
3. What is a diagnostic property of pyroxene?

## Silicate Mineral Group: Double Chain Silicates

Double chain silicates include the **amphibole** family of minerals. There is one amphibole (hornblende) in the mineral kit and the samples vary in colour.

| **Sample M111** | **Mineral name:** |
|---|---|

1. Describe the cleavage of hornblende: ______________________
2. What is the colour of this mineral? ______________________
3. What is a diagnostic property of hornblende?

## Silicate Mineral Group: Isolated Silicates

| **Sample M131** | **Mineral name:** |
|---|---|

The garnet family also contains various kinds of garnet. The most common is almandine, a dark ruby red coloured garnet.

1. Do you see any crystal faces on your sample? ____________
2. What is the hardness of the sample? ______________________
3. What is the lustre of garnet? ______________________
4. What is a diagnostic property of garnet?

| Sample M301 | Mineral name: |
| --- | --- |

Olivine is an igneous mineral that is green, one of the few minerals that can be identified by colour. The samples of olivine in your kit are actually samples of an ultramafic igneous rock composed of many small crystals of olivine.

5. What is the hardness of olivine? ______________________
6. Describe the feel of the sample: _____________________________________________
7. What is a diagnostic property of olivine?

# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 3.1 Silicate Minerals | Silicate minerals are, by far, the most important minerals in Earth's crust. They all include silica tetrahedra (four oxygens surrounding a single silicon atom) arranged in different structures (chains, sheets, etc.). Some silicate minerals include iron or magnesium and are called ferromagnesian silicates. |
| Lab 3 Exercises | The best way to learn mineral identification is to practice by examining the mineral samples in your Mineral Kit 1 and 2. It is important to know all the properties of each mineral in your kits, but especially the diagnostic properties that are most helpful for identifying each mineral. Remember, different samples of the same mineral may not always look exactly the same, but their other physical properties (e.g, hardness, cleavage, lustre) will be consistent. |

# LAB 4: IGNEOUS ROCKS

## Lab Structure

| | |
|---|---|
| Recommended additional work | None |
| Required materials | Mineral ID kit, Rock Kits 1 and 2, pencil |

*Learning Objectives*

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Describe, in general terms, the range of chemical compositions of magmas.
- Discuss the processes that take place during the cooling and crystallization of magma, and the typical order of mineral crystallization according to the Bowen reaction series.
- Describe the origins of phaneritic, porphyritic, and vesicular rock textures.
- Apply the criteria for igneous rock classification based on mineral proportions.
- Use observations of mineralogy and texture to correctly identify and name an igneous rock.

## Key Terms

- Magma
- Lava
- Partial melting
- Crystallization
- Intrusive
- Extrusive
- Felsic
- Intermediate
- Mafic
- Ultramafic
- Phaneritic
- Aphanitic
- Porphyritic
- Vesicular
- Glassy
- Phenocrysts
- Groundmass

A rock is a consolidated mixture of minerals. By *consolidated*, we mean hard and strong; real rocks don't fall apart in your hands! A *mixture of minerals* implies the presence of more than one mineral grain, but not necessarily more than one type of mineral. A rock can be composed of only one type of mineral (e.g., limestone is commonly made up of only calcite), but most rocks are composed of several different minerals. A rock can also include non-minerals, such as fossils or the organic matter within a coal bed or in some types of mudstone.

Rocks are grouped into three main categories based on how they form:

1. **Igneous:** formed from the cooling and crystallization of magma (molten rock)
2. **Sedimentary**: formed when weathered fragments of other rocks are buried, compressed, and cemented together, or when minerals precipitate directly from solution
3. **Metamorphic**: formed by alteration (due to heat, pressure, and/or chemical action) of a pre-existing igneous or sedimentary rock

For the next few weeks you will learn about each of these categories of rock in the lab, beginning with igneous rocks in Lab 4. You will practice identifying minerals and textures, and you will use your observations to classify samples of rocks. Finally, by Lab 6, you will use the processes of the rock cycle to link all three categories of rocks together.

# Lab 4 Exercises

## Classifying Rocks

**<u>All</u>** rocks are classified by just **<u>two</u>** characteristics: texture and mineralogy. The 20 or so minerals which form most rocks are already very familiar to you, the remaining 6000 are not very common and not significant in rock classification, and you can manage in this course without being able to identify them.

The two main textural terms you will use as you examine rocks in labs 4, 5 and 6 are:

**Crystalline**: consisting of a network of interlocking crystals. Igneous, sedimentary and metamorphic rocks may have a crystalline texture.

**Clastic**: consisting of grains eroded from pre-existing rocks. These grains have been transported at least some distance from their place of origin. Only some sedimentary rocks have a clastic texture.

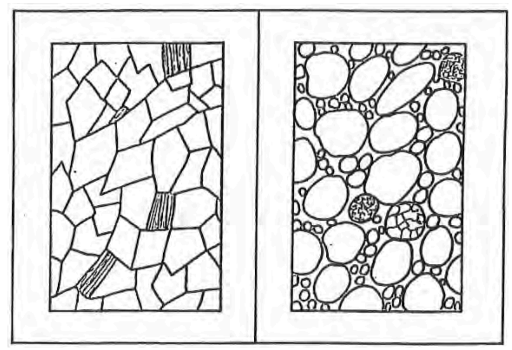


*Figure A: (left) crystalline texture produced by a mosaic of interlocking crystals, and (right) clastic texture composed of individual grains bonded by a chemical cement. Grains may consist of a single mineral, or fragments from pre-existing rocks.*

It is essential that you are able to recognize these textures (Figure A). They form the major division between many rocks. Failure to differentiate between a crystalline versus a clastic texture could result in you being responsible for drilling through granite instead of sandstone!

1. Examine samples R2, R151, and R281 and identify the texture of each sample to complete the table below.

| | |
|---|---|
| **Sample R2** | **Texture:** |
| **Sample R151** | **Texture:** |
| **Sample R281** | **Texture:** |

The exercises below will guide you through the igneous rock samples in Rock Kits 1 and 2. Review the background information presented in Chapters 4.1 to 4.3 before you begin these exercises. You may wish to consult the Rock Classification Tables at the back of this manual as you complete the exercises below.

### *Tips for Identifying Igneous Rocks*

- Your first step when examining any igneous rock is to look closely at the size of the crystals and to determine if its texture is **aphanitic** (individual crystals are too fine to be visible with the naked eye), **phaneritic** (individual crystals are visible with the naked eye), or **porphyritic** (crystals of two or more distinctly different sizes present). If the sample contains no crystals at all and has a vitreous lustre, its texture can be described as glassy. If the sample contains gas bubbles called **vesicles**, its texture is **vesicular**.
- If the sample is phaneritic, or contains **phenocrysts**, try to identify the minerals within the sample.

This will be tricky, as the crystals are much smaller than the samples you examined in Labs 2 and 3. Make sure you examine the sample carefully with your hand lens. You will see much more than with your naked eye alone!

- Start by asking yourself, "how many different minerals can I see in this sample?" and make a short list of the physical properties you observe (e.g., colour, lustre, cleavage).
- Use your observations and the mineral identification tables to identify the minerals present, and make an estimate of their proportions using Figure A in the Rock Classification Tables appendix as a guide. Some mineral-specific hints are outlined here:
    - Quartz crystals come in many colours, but quartz always has vitreous lustre and is often translucent.
    - Potassium feldspar (K-feldspar) is commonly white or pink in colour, and is often opaque (milky) to semi-translucent.
    - Plagioclase feldspar is commonly white to dark bluish grey in colour (depending on the composition), is often opaque (milky) to semi-translucent, and has striations.
    - Examining a weathered surface can help to differentiate quartz from feldspar minerals: feldspars chemically weather tend to look chalky and dull (see Figure 5.1.4), whereas quartz always looks glassy. If you look for freshly broken surfaces or edges of the sample you may even see that the feldspar crystals break along cleavage planes while the quartz crystals have conchoidal fracture.
    - Muscovite (colourless, translucent) and biotite (dark brown to black) both appear as thin sheets or flakes.
    - To tell biotite from other ferromagnesian minerals, test its hardness with a steel file or thin knife: biotite has a Mohs hardness of ~ 2.5-3 whereas amphibole and pyroxene are much harder (H = 5-6).
    - It can be difficult to tell amphibole from pyroxene in rocks, as they have similar hardnesses, form blocky crystals, and can be found in similar colours (shades of green to black). Look closely for cleavage: amphibole has 2 planes not at 90°, whereas pyroxene has 2 planes at 90°. If you are unsure whether a ferromagnesian mineral is amphibole or pyroxene and have already identified the other minerals present, it may help to use Figure 4.3.1 as a guide. For example, if you have identified K-feldspar, quartz, and white plagioclase in a sample, chances are the dark coloured blocky mineral you see is amphibole and not pyroxene. Why? Because a **felsic** magma that is crystallizing K-feldspar and quartz will not normally also crystallize pyroxene.
    - Olivine can be distinguished by its vitreous lustre and olive green to yellow-green colour. Caution: weathered olivine may appear dull or rusty (from iron oxide staining).
- If the sample is aphanitic, use the colour of a fresh surface to estimate the composition: felsic rocks are light-coloured (beige, buff, tan, pink, white, pale grey) whereas mafic rocks are dark-coloured (dark grey to black).
- Finally, combine your observations of texture and composition, and use Figure B in the Rock Classification Tables appendix to name the rock.
    - If the sample is porphyritic with an aphanitic **groundmass**, identify the phenocryst mineral(s), interpret the overall composition based on the colour of the groundmass, and name the rock as [phenocryst mineral name] porphyritic [rock name]. For example, a porphyritic volcanic rock with pyroxene phenocrysts in a dark grey aphanitic groundmass is a pyroxene porphyritic basalt.
    - Rock names can likewise be modified by other textural terms (e.g., vesicular basalt).

2. Remove samples R1, R2, R11, R21, R31, R41, R42, R51, R61, and R71 from Rock Kit 1 and place the samples on the table in front of you. Arrange these samples according to colour, in a line or into groups. What does the colour of an igneous rock tell you?

3. Keeping the same colour groups you just arranged, within each group arrange the same set of samples according to their grain size (the size of the crystals that make up these rocks). As you examine each sample decide whether:

- all or most of the crystals are large enough for you to see with your naked eye,
- all or most of the crystals are too fine to see clearly with your naked eye, or
- there are no crystals at all (sample is glassy).

4. What does grain size tell you about the cooling history of an igneous rock?

---

The groups of igneous rocks you just arranged should reflect the classification presented in Figure B in the Rock Classification Tables. Now that you have had a chance to compare all the samples, let's examine each sample in more detail.

| | |
|---|---|
| **Sample R1** | **Rock name:** |
| **Sample R2** | **Rock name:** |

5. It can be useful to look at both weathered and fresh (unweathered) surfaces of a rock sample, as both can be useful when identifying minerals. However, it is important to make note of what type of surface you are describing in your notes. Are you looking at a fresh or a weathered surface? _______________________
6. Are these rocks comprised of grains or crystals? _______________________
7. These samples are both crystalline rocks (in contrast to clastic rocks which you will be examining in lab 5). Notice the prominent cleavage faces which can be seen on some of the crystals. Which mineral(s) is (are) showing cleavage?

---

8. Are these rocks aphanitic or phaneritic? _______________________
9. Are the crystals all of relatively similar size or obviously different sizes? __________________________
10. Describe the colour of the rock: _______________________________________________
11. What do you estimate is the percentage of light (non-ferromagnesian) and dark-coloured (ferromagnesian) minerals?

| | | | |
|---|---|---|---|
| Non-ferromagnesian: | % | Ferromagnesian: | % |

12. List below the minerals which you recognize in order of abundance (remember to use your hand lens).

---

---

13. Which mineral is responsible for unique colour of sample R2? _______________________

| | |
|---|---|
| **Sample R11** | **Rock name:** |

14. Are you looking at a fresh or a weathered surface? ______________________
15. Choose a term which best describes the texture of this rock: ______________________
16. Describe the colour of this rock (light/intermediate/dark):______________________
17. What do you think is the basic difference between specimens R1 and R11?

______________________

______________________

18. Did sample R11 cool slowly (intrusive) or rapidly (extrusive) compared to R1? ______________________

| **Sample R21** | **Rock name:** |
|---|---|

19. Are you looking at a fresh or a weathered surface? ______________________
20. Which textural term best describes this rock?______________________
21. The larger crystals in the aphanitic groundmass are called ______________________.
22. Do you see cleavage planes on any of the larger crystals? ______________________
23. What size (in mm) are the larger crystals? ______________________
24. Are these crystals all the same mineral? ______________________
25. Describe the overall colour of the rock (light/intermediate/dark): ______________________

| **Sample R31** | **Rock name:** |
|---|---|

26. Are you looking at a fresh or a weathered surface? ______________________
27. Is the rock aphanitic or phaneritic? ______________________
28. Does the textural term, 'porphyritic' apply to this rock? ______________________
29. Did the rock cool slowly or rapidly? ______________________
30. List the minerals in this rock in order of abundance:

______________________

______________________

31. What do you estimate is the percentage of light and dark-coloured minerals?

| Non-ferromagnesian: | % | Ferromagnesian: | % |
|---|---|---|---|

32. Do you see cleavage planes on any of the minerals? ______________________If so, which ones? ________
______________________________________

33. Describe the colour of this rock (compare the colour to that of R1 and R51):

______________________

| **Sample R51** | **Rock name:** |
|---|---|

34. Are you looking at a fresh or a weathered surface? ______________________
35. Which textural term best describes this rock?______________________

36. Do any of the crystals exhibit cleavage planes? ______________________ If so, which ones? ____________ ______________________________________________________

37. What do you estimate is the percentage of light and dark-coloured minerals?

| | | | |
|---|---|---|---|
| Non-ferromagnesian: | % | Ferromagnesian: | % |

38. Would you say that texture (grain size) or mineralogy (mineral composition) is the basic difference between R1, R31, and R51?

| | |
|---|---|
| **Sample R41** | **Rock name:** |

39. Which textural term best describes this rock? ______________________
40. Do you see any phenocrysts in this rock? ______________________
41. Describe the colour of the rock on a fresh surface ______________________
42. Is this rock intrusive or extrusive? ______________________ What evidence supports your answer? _____ _______________________________________

43. What is the basic difference between this rock and R51?

| | |
|---|---|
| **Sample R42** | **Rock name:** |

44. Which textural term applies to this sample? ______________________
45. What are the small spherical cavities occurring throughout the rock called, and how did they form?

46. What is the difference between this rock and R41?

| | |
|---|---|
| **Sample R61** | **Rock name:** |

47. Describe the texture of this rock (Hint: what substance does it resemble):

48. Can you see the individual crystals in this rock? __________
49. What term best describes the type of fracture of this rock? ________________________________________ ____

This is a sample of **obsidian** and its texture is due to the super cooling of magma, resulting in a non-crystalline, glassy texture.

50. Compare this specimen to R71 (**pumice**) which is also a type of glass. How do they differ?

## Media Attributions

- Figure A: 

# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 4.1 Magma and Magma Formation | Magma is molten rock, and in most cases, it forms from partial melting of existing rock. The two main processes of magma formation are decompression melting and flux melting. Magmas range in composition from ultramafic to felsic. Mafic rocks are rich in iron, magnesium, and calcium, and have around 50% silica. Felsic rocks are rich in silica (~75%) and have lower levels of iron, magnesium, and calcium and higher levels of sodium and potassium than mafic rocks. Intermediate rocks have compositions between felsic and mafic. |
| 4.2 Crystallization of Magma | As a body of magma starts to cool, the first process to take place is the polymerization of silica tetrahedra into chains. This increases the magma's viscosity (makes it thicker) and because felsic magmas have more silica than mafic magmas, they tend to be more viscous. The Bowen reaction series allows us to predict the order of crystallization of magma as it cools. |
| 4.3 Classification of Igneous Rock | Igneous rocks are classified based on their mineral composition and texture. Felsic igneous rocks have less than 20% ferromagnesian silicates (amphibole and/or biotite) plus varying amounts of quartz and both potassium and plagioclase feldspars. Mafic igneous rocks have more than 50% ferromagnesian silicates (primarily pyroxene) plus plagioclase feldspar. Most intrusive igneous rocks are phaneritic (crystals are visible to the naked eye), whereas most extrusive (volcanic) rocks are aphanitic (crystals are too small to be seen with the naked eye). If there were two stages of cooling (slow then fast), the texture may be porphyritic (large crystals in a matrix of smaller crystals). Gas bubbles "frozen" in an igneous rock are called vesicles, and the textural term for a rock with vesicles is vesicular. |
| Lab 4 Exercises | The best way to learn rock identification is to practice by examining the samples in your Rock Kit 1 and 2. Igneous rocks are classified according to their mineral composition (or colour, in the case of aphanitic rocks), and texture (size of the crystals). Knowing the diagnostic properties of the minerals within an igneous rock help you identify its composition as mafic, intermediate, or felsic. Just as with mineral samples, different samples of the same rock may not always look exactly the same (e.g., pink versus white granite), but they can always be identified by closely examining the mineral composition and texture. |

# LAB 5: SEDIMENTS AND SEDIMENTARY ROCKS

## Lab Structure

| | |
|---|---|
| Recommended additional work | None |
| Required materials | Mineral ID kit, Rock Kits 1 and 2, Mineral Kits 1 and 2, pencil |

*Learning Objectives*

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Describe the main processes of mechanical weathering, and the types of materials that are produced when mechanical weathering predominates.
- Describe the main processes of chemical weathering, and the products of chemical weathering of minerals such as feldspar, ferromagnesian silicates, and calcite.
- Explain the type of weathering processes that are likely to have taken place to produce a particular sediment deposit.
- Describe the differences between cobbles, pebbles, sand, silt, and clay and explain the relationship between clast size and the extent to which clasts can be transported by moving water or by wind.
- Identify and describe the characteristics of the various types of clastic and chemical sedimentary rock based on their texture and mineralogy.

## Key Terms

- Sediment
- Sedimentary rock
- Mechanical weathering
- Chemical weathering
- Erosion
- Deposition
- Lithification
- Clast
- Boulder
- Cobble
- Pebble
- Granule
- Sand
- Silt
- Clay
- Cement
- Crystalline
- Clastic
- Oolitic
- Amorphous
- Bioclastic
- Fossiliferous

*Figure 5.0.1: The Hoodoos, near Drumheller, Alberta, have formed from the differential weathering of sedimentary rock that was buried beneath other rock for close to 100 Ma.*

**Weathering** is what takes place when a body of rock is exposed to the "weather"—in other words, to the forces and conditions that exist at Earth's surface. With the exception of volcanic rocks and some sedimentary rocks, most rocks are formed at some depth within the crust. There they experience relatively constant temperature, high pressure, no contact with the atmosphere, and little or no moving water. Once a rock is exposed at the surface, which is what happens when the overlying rock is eroded away, conditions change dramatically. Temperatures vary widely, there is much less pressure, oxygen and other gases are plentiful, and in most climates, water is abundant (Figure 5.0.1). The various processes related to uplift and weathering are summarized in the rock cycle in Figure 5.0.2.

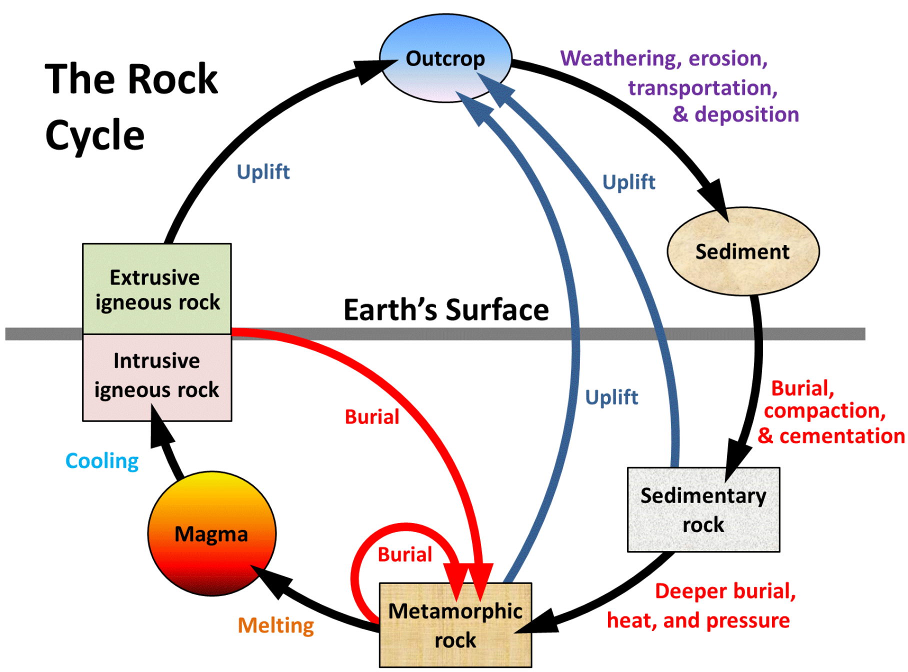



*Figure 5.0.2: The rock cycle, showing the processes related to sedimentary rocks on the right-hand side.[Image description]*

In this chapter, we will cover three core concepts: the formation of sediment through the weathering of rocks at the Earth's surface, the formation of sedimentary rocks from accumulated sediments, and the classification of various types of sedimentary rocks. The weathering and erosion of existing rocks at the Earth's surface are the first two steps in the transformation of existing rocks into sedimentary rocks. The remaining steps in the formation of sedimentary rocks-transportation, deposition, burial, and lithification (Figure 5.0.2) – will be discussed in more detail in chapter 5.3.

In this course, we divide sedimentary rocks into two main types: **clastic** and **chemical**. Clastic sedimentary rocks are mainly composed of material that has been transported as solid fragments (**clasts**). Chemical sedimentary rocks are mainly composed of material that has been transported as ions in solution. It's important *not* to assume that mechanical weathering leads only to clastic sedimentary rocks, while chemical weathering leads only to chemical sedimentary rocks. In most cases, millions of years separate the weathering and depositional processes, and both types of sedimentary rocks tend to include at least some material derived from both types of weathering.

## Image Descriptions

**Figure 5.0.2 image description:** "The Rock Cycle." The rock cycle takes place both above and below the Earth's surface. The rock deepest beneath the Earth's surface and under extreme heat and pressure is metamorphic rock. This metamorphic rock can melt and become magma. When magma cools, if below the Earth's surface it becomes "intrusive igneous rock." If magma cools above the earth's surface it is "extrusive igneous rock" and becomes part of the outcrop. The outcrop is subject to weathering and erosion, and can be moved and redeposited around the earth by forces such as water and wind. As the outcrop is eroded, it becomes sediment which can be buried, compacted, and cemented beneath the Earth's surface to become sedimentary rock. As sedimentary rock gets buried deeper and comes under increased heat and pressure, it changes into a metamorphic rock. Rocks in the rock cycle do not always make a complete loop. It is possible for sedimentary rock to be uplifted back above the Earth's surface and for intrusive and extrusive igneous rock to be reburied and became metamorphic rock. [Return to Figure 5.0.2]

## Media Attributions

- Figures 5.0.1, 5.0.2: 

# Lab 5 Exercises

The exercises below will guide you through the sedimentary rock samples in Rock Kits 1 and 2. Review the background information presented in Chapters 5.1 to 5.5 before you begin these exercises. You may wish to consult the Rock Classification Tables at the back of this manual as you complete the exercises below.

## *Tips for Classifying Sedimentary Rocks*

- Your first step when examining any sedimentary rock is to determine if its texture is **clastic** or **crystalline**.
- If the texture is clastic, next determine the predominant size of the grains by looking closely through your hand lens and using the grain size chart (see Table A in the Rock Classification Tables appendix).
- Next, describe the sorting, and the shape (roundness) of the grains (Figure C in the Rock Classification Tables appendix). Remember that you are not describing the shape or size of the sample, but of the grains within it!
- If the texture is crystalline, test the sample with a drop (only a drop!) of dilute HCl. If the rock reacts with HCl, look carefully to determine what exactly is reacting (e.g., cement between grains of quartz sand? The entire sample of limestone?).
- Quartz grains come in many colours, but always have vitreous lustre.
- Feldspar grains are commonly white or pink in colour, and in very coarse-grained clastic sedimentary rocks, you may even see feldspar grains broken along cleavage planes. Feldspar grains that have been chemically weathered tend to look chalky and dull (see Figure 5.1.4), which can help you differentiate them from quartz grains.

1. Using your hand lens, carefully examine samples R151, R161, R162, and R181 from your Rock Kit to complete the table below. The example provided indicates the level of detail expected of your observations.

| **Sample #** | **Grain Size (mm)** | **Energy Level** | **Roundness** | **Sorting** | **Composition (grains and cement)** | **Rock Name** |
|---|---|---|---|---|---|---|
| **Example** | 0.5-2 mm (sand) | Moderate | Sub-rounded | Moderately sorted | 65% quartz, 35% rock fragments, calcite cement | Lithic arenite |
| **R151** | | | | | | |
| **R161** | | | | | | |
| **R162** | | | | | | |
| **R181** | | | | | | |

2. Are all four samples in the table above chemical or detrital (clastic) in origin? How can you tell?

3. Indicate where on the diagram each of the samples from the table above is most likely to have formed by considering the grain size, roundness, sorting, and composition.

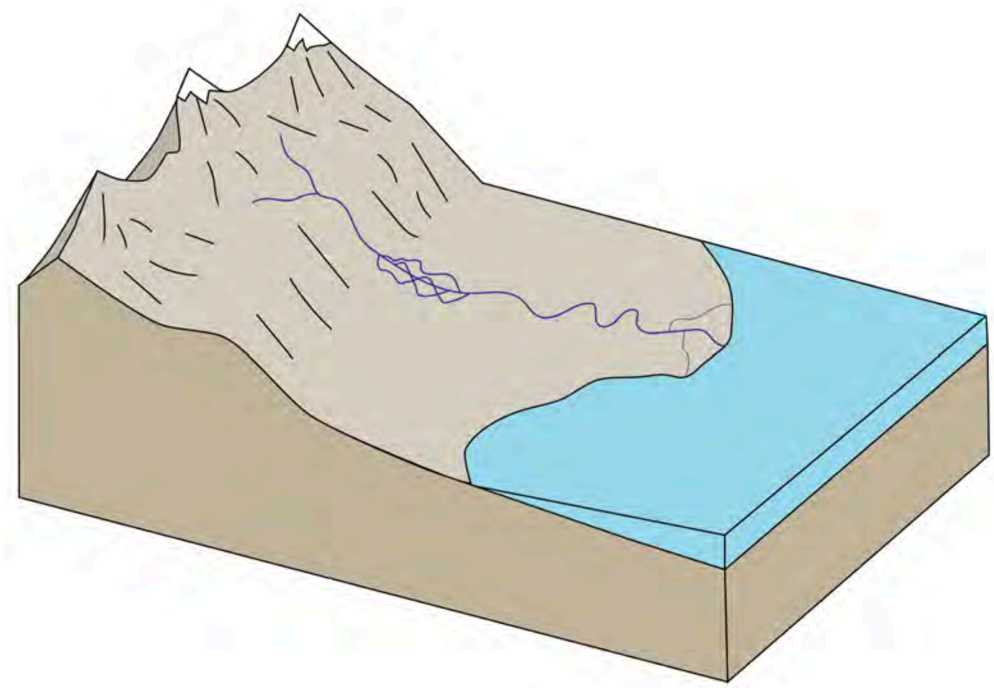


*Figure A*

4. Imagine a large granite **pluton** has been uplifted and exposed at the surface. Imagine that this granite is the source material for samples R161 and R162.

a) List the minerals you would expect to find in this granite, and their typical weathering products.

b) If these two samples originated from the same source material, explain what process(es) are responsible for the key difference(s) between them? Hint: examine your answers in the table above.

5. Examine chemical sedimentary rock samples RI91, R201, R211, R221, R231, R251, R261, R271, and R281. In the table below, name the mineral and chemical sedimentary rock(s) from your rock kits that correspond to the composition provided. As you examine each rock sample, think about what physical properties the mineral and the rock have in common. You may want to review the physical properties of minerals summarized in Labs 2 and 3, and in the mineral identification tables.

| Composition | Mineral Name | Rock Sample # | Rock Name | Diagnostic Properties Common to Both Rock and Mineral |
|---|---|---|---|---|
| **$CaCO_3$** | | | | |
| **$SiO_2$** | | | | |
| **NaCl** | | | | |
| **$CaSO_4 \cdot H_2O$** | | | | |
| **C (mostly)** | N/A | | | |

6. Examine sample R201. What shape are the grains? ___________________________

7. The small rounded grains that you see are called **ooids**, and the textural term for a rock with ooids is ____ ____________________.

8. How do you think the ooids formed?

___

___

9. Name this rock: ____________________________________________

10. Examine sample R211 (coquina). Look closely at the larger grains. What would be a more appropriate term than ‘grains’?

___

11. What is the main component of the rock? ____________________________

12. Compare samples R211 and R221. How are these two samples similar? How do they differ, and how would you distinguish one from the other?

___

___

13. Examine sample R231. This is a type of limestone known as **chalk**. It is composed mainly of shelly remains of microscopic animals. Scratch this sample with your fingernail. Why does it seem so much softer than a crystal of calcite?

14. Examine sample R251. The black colour is due to the very high organic content of the rock. This type of rock is combustible. Name this rock: ________________

15. How does this type of sedimentary rock form?

16. Examine samples R271 and R281. These are both examples of **evaporites** – they have formed by precipitation of crystals from a solution. In what ways do these two different samples differ?

17. Studying sedimentary rocks provides geologists with a window into the past. Simple observations about composition and texture of a rock sample can give a geologist important clues about the ancient environment in which a sedimentary rock formed. Use your observations of sedimentary rock samples R151, R161, R181, R221 and R281, and the information provided in Chapter 5.5 to complete the table below. You should find more than one possible depositional environment for most samples. In higher level geology courses, you will learn additional features to observe to narrow down the possible depositional environments for a sample.

| Sample | Possible environment(s) of deposition | Evidence |
|---|---|---|
| R151 | | |
| R161 | | |
| R181 | | |
| R281 | | |
| R221 | | |

## Media Attributions

- Figure A: © Siobhan McGoldrick. CC BY.

# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 5.1 Weathering | Rocks weather when they are exposed to surface conditions, which in most case are quite different from those at which they formed. The main processes of mechanical weathering include exfoliation, freeze-thaw, salt crystallization, and the effects of plant growth. Chemical weathering takes place when minerals within rocks are not stable in their existing environment. Some of the important chemical weathering processes are hydrolysis of silicate minerals to form clay minerals, oxidation of iron in silicate and other minerals to form iron oxide minerals, and dissolution of calcite. |
| 5.2 The Products of Weathering and Erosion | The main products of weathering and erosion are grains of quartz (because quartz is resistant to chemical weathering), clay minerals, iron oxide minerals, rock fragments, and a wide range of ions in solution. Without weathering, there would not be sediment available to eventually form sedimentary rocks! |
| 5.3 Clastic Sedimentary Rocks | Sedimentary clasts are classified based on their size, and variations in clast size and shape have important implications for transportation and deposition. Clastic sedimentary rocks are classified based on their grain size and composition. Clast size, sorting, composition, and shape are important features that allow us to differentiate clastic rocks and understand the processes that took place during their deposition. |
| 5.4 Chemical Sedimentary Rocks | Chemical sedimentary rocks form from ions that were transported in solution, and then converted into minerals by biological and/or chemical processes. The most common chemical rock, limestone, typically forms in shallow tropical environments, where biological activity is a very important factor. Names of limestones can be modified with textural terms like crystalline, oolitic, or fossiliferous. Chert is a deep-ocean sedimentary rocks. Evaporites (rock salt and rock gypsum) form where the water of lakes and inland seas becomes supersaturated due to evaporation. Coal forms in swamps from decaying plant remains. |
| 5.5 Depositional Environments and Sedimentary Basins | There is a wide range of depositional environments, both on land (glaciers, lakes, rivers, etc.) and in the ocean (deltas, reefs, shelves, and the deep-ocean floor). In order to be preserved, sediments must accumulate in long-lasting sedimentary basins, most of which form through plate tectonic processes. |
| Lab 5 Exercises | The best way to learn rock identification is to practice by examining the samples in your Rock Kit 1 and 2. The first step when examining a sedimentary rock is to identify the texture. Clastic sedimentary rocks have clastic textures, and are classified based on grain size, and for sandstones, also by composition. Chemical sedimentary rocks are often monomineralic and are classified based on composition. Chemical sedimentary rocks can have a range of textures (crystalline, clastic, bioclastic, fossiliferous, oolitic, and amorphous). Knowing the diagnostic properties of the main minerals that form chemical sedimentary rocks will help you correctly identify the rock. Just as with mineral samples, different samples of the same rock may not always look exactly the same (e.g., tan versus blue-grey crystalline limestone), but they can always be identified by closely examining the mineral composition and texture. |

# LAB 6: METAMORPHIC ROCKS AND THE ROCK CYCLE

## Lab Structure

| | |
|---|---|
| Recommended additional work | Yes – review rock and mineral ID in preparation for Test 2 |
| Required materials | Mineral ID kit, Rock Kits 1 and 2, hand lens, pencil |

*Learning Objectives*

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Summarize the factors that influence the nature of metamorphic rocks and explain why each one is important.
- Recognize foliation and explain the mechanisms for its formation in metamorphic rocks.
- Classify metamorphic rocks on the basis of their texture and mineral content, and explain the origins of these differences.
- Describe the various settings in which metamorphic rocks are formed and the links between plate tectonics and metamorphism.
- Describe the rock cycle and the types of processes that lead to the formation of igneous, sedimentary, and metamorphic rocks.

## Key Terms

- Metamorphism
- Metamorphic grade
- Geothermal gradient
- Index minerals
- Protolith
- Recrystallization
- Foliation
- Slaty
- Schistose
- Gneissic
- Massive

# Lab 6 Exercises

## Part I: Metamorphic Rocks

The exercises below will guide you through the metamorphic rock samples in Rock Kits 1 and 2. Review the background information presented in Chapters 6.1 and 6.2 before you begin these exercises. You may wish to consult the Rock Classification Tables at the back of this manual as you complete the exercises below.

### *Tips for Classifying Metamorphic Rocks*

- Your first step when examining a metamorphic rock is to determine if its texture is **foliated** or **massive**.
- If the rock is foliated, next determine the type of foliation:
  - **Slaty** foliations are flat, smooth surfaces along which a slate breaks. They might have a slightly shinier lustre than a shale.
  - Larger crystals of micas that define a **schistose** foliation give it a shiny, wavy appearance and any sheet-like or elongate minerals will be aligned in a preferred orientation.
  - **Gneissic** foliation, or gneissic banding, is defined by segregated bands of light-coloured quartz and feldspars and dark-coloured **ferromagnesian** minerals.
- If the texture is massive, test the sample with a drop of dilute HCl. **Marble** reacts with HCl just like its protolith – limestone!
- If the sample is massive and does not react with HCl, try testing the hardness. **Quartzite** is composed predominantly of quartz, giving it a hardness ~7.
- Lastly, if the metamorphic rock is foliated but has a distinctly green-colour to it, and contains abundant ferromagnesian minerals chlorite and green amphibole, it is called a **greenschist**.
- Figure E and Table D in the Rock Classification Tables appendix may be helpful resources as you complete these lab exercises.

1. The best way to really appreciate the metamorphic changes to a rock is to meet its parent! Examine each of the sample pairs listed below. Each pair contains a metamorphic rock and its **protolith** (parent rock). Identify which of the two samples is the metamorphic rock, and then carefully compare the two. In what ways are the metamorphic rock and its protolith similar? In what ways do they differ? Record your observations in the table below.

- Pair A: R221 and R361
- Pair B: R301 and R181
- Pair C: R1 and R331
- Paid D: R351 and R161

| | Name of protolith | Name of metamorphic rock | **Observations** (how does the metamorphic rock differ from its protolith?) |
|---|---|---|---|
| **Pair A** | | | |
| **Pair B** | | | |
| **Pair C** | | | |
| **Pair D** | | | |

2. Examine samples R181, R301, R321, R331, and R332. These samples show the progression of changes from a protolith (shale) to a high grade metamorphic rock (gneiss). Complete the table below by recording the changes you observe in mineralogy and texture with increasing metamorphism. For the changes in mineralogy, record what new minerals you see and note any minerals that have disappeared. For the changes in texture, look for changes in grain size or the development of a foliation.

| | **Changes in mineralogy** | **Changes in texture** |
|---|---|---|
| **Shale to slate**<br><br>(R181 to R301/R302) | | |
| **Slate to schist**<br><br>(R301/R302 to R321) | | |
| **Schist to gneiss**<br><br>(R321 to R331/R332) | | |

3. This progression of foliated metamorphic rocks from slate to gneiss is typical of mudrocks that are metamorphosed during **regional metamorphism** with a typical **geothermal gradient**. Using Figure 6.1.6 and Figure E in the Rock Classification Tables as a guide, complete the table below to summarize the range of temperatures and depths (pressure) responsible for the metamorphism of samples R301, R321, and R332.

| **Sample #** | **Approx. temperature (°C)** | **Approx. Depth (km)** | **Metamorphic Grade** (low, intermediate, high) |
|---|---|---|---|
| **R301** | | | |
| **R321** | | | |
| **R332** | | | |

4. Which two samples in your Rock Kits 1 and 2 represent non-foliated (or **massive**) metamorphic rocks? ___ ________________________________

5. Do these two samples exhibit crystalline or clastic textures? ____________________

6. Examine sample R351. Try to scratch this sample with the tools from your mineral ID kit. How hard is this sample? ______________

7. Based on your answer above, and any other physical properties you observe, name the main mineral(s) present in this rock: ____________________________________________________________

8. Examine sample R361. Try to scratch this sample with the tools from your mineral ID kit. How hard is this sample? ______________

9. Place a small drop of HCl on a fresh surface of the sample. What happens? __________________________ _________________________

10. On the basis of these two tests name the main mineral present in this rock: _____________________

11. Metamorphism may affect the texture or the mineral composition or both of these properties of the protolith. Do samples R351 and R361 have the same mineral composition as their respective sedimentary protoliths? Do they have the same texture? Explain your answers.

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

## Part II: The Rock Cycle

The exercises below are a review of the rock cycle processes by which one type of rock is transformed into another over geological time. You will review all the rock samples in Rock Kits 1 and 2 that you have examined to date in preparation for Test 2. Review the background information presented in Chapter 6.3 before you begin these exercises. To benefit the most from these review exercises, remove all your rock samples from the Rock Kits and set the empty kits aside, so that you cannot see the names of the rocks.

All rocks are connected through the rock cycle. Any rock that you see today will at some point in the future be transformed into a different rock through the rock cycle (see Figure 6.3.1). This exercise focuses on the ***processes*** that are responsible for the transformation of one rock type into another. As a starting point, summarize the main processes involved in the formation of the three main categories of rock:

- Igneous:

- Sedimentary:

- Metamorphic:

The example presented below illustrates how you should complete question 12, by explaining the processes that formed the rocks in the second column. This example begins with granite, and the processes responsible for the formation of the granite are explained first. Then, the processes that explain how granite is transformed into quartz sandstone are outlined, and so on.

| Order | Rock Name | Sample # | Rock Cycle Processes Responsible |
|---|---|---|---|
| **1** | **Granite** | R1 | Partial melting of pre-existing rock to generate magma. Felsic magma cools and crystallizes at depth to form granite, a felsic intrusive igneous rock. |
| **2** | **Quartz sandstone** | R161 | Granite is uplifted to surface, chemically and mechanically weathered, and eroded. Sand-sized grains of quartz, feldspar and some ferromagnesian minerals are transported. Feldspars and ferromagnesian minerals chemically weather to form clay minerals and ions in solution. Quartz grains become more rounded and better sorted with transport. Eventually quartz grains are deposited in a moderate to high energy environment (depending on grain size). Grains of quartz are lithified into sandstone through burial by other sediments, compaction, and cementation by mineral(s) precipitated from a fluid. |
| **3** | **Quartzite** | R351 | Quartz sandstone is metamorphosed through regional or contact metamorphism. Grains of quartz recrystallize into coarser grains to form a crystalline texture. |

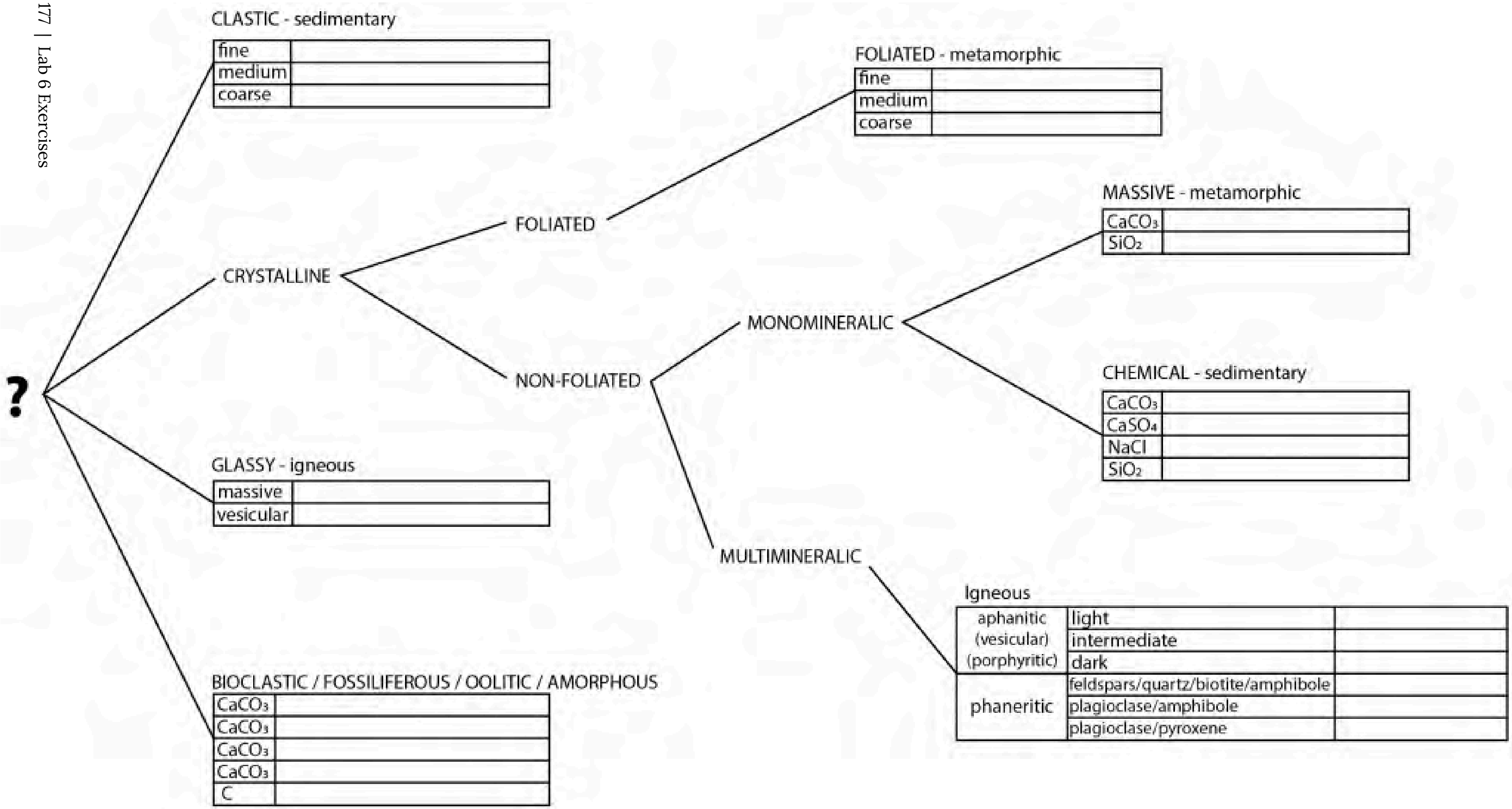
12. For each of the rocks specified below, find the corresponding rock sample from your collection of rocks. Remember, for this to be an effective review activity, do this without looking at the rock names in the kit! Complete the table with the appropriate sample number, and explain the processes from the rock cycle that have transformed the previous sample into the present sample. Begin by explaining how pebble-sized clasts of basalt formed, and then how shale could form from those basalt pebbles, and so on.

| Order | Rock Name | Sample # | Rock Cycle Processes Responsible |
|---|---|---|---|
| 1 | Basalt pebbles (sediment) | N/A | |
| 2 | Shale | | |
| 3 | Garnet gneiss | | |
| 4 | Diorite | | |

## Part III: Rock Review

13. Use the flow chart below to review igneous, sedimentary, and metamorphic rocks from Labs 4-6. This review will help you prepare for Test 2. The words “fine”, “medium”, and “coarse” on the flow chart refer to grain size. Chemical formulae are listed for any **monomineralic** rocks. The words “light”, “inter-

mediate", and "dark" refer to the colour (and therefore composition) of aphanitic igneous rocks.


?
CLASTIC - sedimentary
fine
medium
coarse
CRYSTALLINE
FOLIATED
FOLIATED - metamorphic
fine
medium
coarse
NON-FOLIATED
MONOMINERALIC
MASSIVE - metamorphic
CaCO₃
SiO₂
CHEMICAL - sedimentary
CaCO₃
CaSO₄
NaCl
SiO₂
MULTIMINERALIC
Igneous
aphanitic
(vesicular)
(porphyritic)
light
intermediate
dark
phaneritic
feldspars/quartz/biotite/amphibole
plagioclase/amphibole
plagioclase/pyroxene
GLASSY - igneous
massive
vesicular
BIOCLASTIC / FOSSILIFEROUS / OOLITIC / AMORPHOUS
CaCO₃
CaCO₃
CaCO₃
CaCO₃
C

# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 6.1 Metamorphism and Plate Tectonics | Metamorphism is controlled by five main factors: the composition of the parent rock, the temperature to which the rock is heated, the amount and type of pressure, the volumes and compositions of aqueous fluids that are present, and the amount of time available for metamorphic reactions to take place. Almost all metamorphism can be explained by plate tectonic processes. Most regional metamorphism takes place in areas where mountain ranges have been created, which are most common at convergent boundaries. Contact metamorphism takes place around magma bodies in the upper part of the crust, which are also most common above convergent boundaries. |
| 6.2 Classification of Metamorphic Rocks | Metamorphic rocks are classified on the basis of texture and mineral composition. Foliation is a key feature of metamorphic rocks formed under directed pressure. Foliated metamorphic rocks include slate, phyllite, schist, and gneiss. Metamorphic rocks that do not tend to be foliated, even if formed under directed pressure, include marble and quartzite. Geologists also classify metamorphic rocks based on some key minerals—such as chlorite, garnet, andalusite, and sillimanite—that form at specific temperatures and pressures. |
| 6.3 The Rock Cycle | The three types of rocks are igneous: formed from magma; sedimentary: formed from fragments of other rocks or precipitation from solution; and metamorphic: formed when existing rocks are altered by heat, pressure, and/or chemical action. The rock cycle summarizes the processes that contribute to cycling of rock material among these three types. The rock cycle is driven by Earth's internal heat, and by processes happening at the surface, which are driven by solar energy. |
| Lab 6 Exercises | Metamorphic rocks are classified according to their mineral composition, and texture (foliated or massive). Knowing the diagnostic properties of the common metamorphic minerals like chlorite, muscovite, biotite, and garnet will help you estimate the metamorphic grade of the rock (low, intermediate, or high grade). Just as with mineral samples, different samples of the same rock may not always look exactly the same, but they can always be identified by closely examining the mineral composition and texture. For example, schist can contain a wide variety of new metamorphic minerals with different colours and shapes, but all schists are characterized by schistose foliation. |

# Review of Minerals and Rocks

*Mineral and Rock Review*

Now that we've covered minerals and all three types of rocks it's important for you to convince yourself that you've got them straight in your mind. As already noted, one of the most common mistakes that geology students make on assignments, tests, and exams is to confuse minerals with rocks and then give a wrong answer when asked to name one or the other based on information provided.

In this exercise you are given a list of names of minerals and rocks and asked to determine which ones are minerals and which are rocks. For those that you think are minerals you should then indicate which mineral group it belongs to (e.g., *oxide*, *sulphate*, *silicate*, *carbonate*, *halide* etc.). For those that you think are rocks, you should describe what type of rock it is (e.g., *intrusive igneous*, *extrusive igneous*, *clastic sedimentary*, *chemical sedimentary*, *foliated metamorphic* and *non-foliated (massive) metamorphic*). If the rock is metamorphic, list its protolith. The answers can be found in Appendix 3.

| **Mineral or rock name** | **Rock or mineral?** | **If it's a mineral, which group does it belong to? If it's a rock, what type is it?** |
|---|---|---|
| Feldspar | | |
| Calcite | | |
| Slate | | |
| Hematite | | |
| Rhyolite | | |
| Sandstone | | |
| Diorite | | |
| Olivine | | |
| Pyrite | | |
| Quartzite | | |
| Granite | | |
| Amphibole | | |
| Conglomerate | | |
| Chert | | |
| Halite | | |
| Gneiss | | |
| Mica | | |
| Pyroxene | | |
| Chlorite | | |
| Limestone | | |
| Andesite | | |

# LAB 7: RELATIVE DATING AND GEOLOGICAL TIME

## Lab Structure

| | |
|---|---|
| Recommended additional work | None |
| Required materials | Pencil |

*Learning Objectives*

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Apply basic geological principles to the determination of the relative ages of rocks.
- Explain the difference between relative and absolute age-dating techniques.
- Summarize the history of the geological time scale and the relationships between eons, eras, periods, and epochs.
- Understand the importance and significance of unconformities.
- Explain why an understanding of geological time is critical to both geologists and the general public.

## Key Terms

- Eon
- Era
- Period
- Relative dating
- Absolute dating
- Isotopic dating
- Stratigraphy
- Strata
- Superposition
- Original horizontality
- Cross-cutting
- Inclusions
- Faunal succession
- Unconformity
- Angular unconformity
- Disconformity
- Nonconformity
- Paraconformity

Time is the dimension that sets geology apart from most other sciences. Geological time is vast, and Earth has changed enough over that time that some of the rock types that formed in the past could not form today. Furthermore, as we've discussed, even though most geological processes are very, very slow, the vast amount of time that has passed has allowed for the formation of extraordinary geological features, as shown in Figure 7.0.1.

*Figure 7.0.1: Arizona's Grand Canyon is an icon for geological time; 1,450 million years are represented by this photo. The light-coloured layered rocks at the top formed at around 250 Ma, and the dark rocks at the bottom (within the steep canyon) at around 1,700 Ma.*

We have numerous ways of measuring geological time. We can tell the relative ages of rocks (for example, whether one rock is older than another) based on their spatial relationships; we can use fossils to date sedimentary rocks because we have a detailed record of the evolution of life on Earth; and we can use a range of isotopic techniques to determine the actual ages (in millions of years) of igneous and metamorphic rocks. We will explore the use of fossils in dating sedimentary rocks, and interpreting past changes in climate and depositional environment through geologic time in the subsequent geology course, GEOL 1103 – Earth Through Time.

But just because we can measure geological time doesn't mean that we understand it. One of the biggest hurdles faced by geology students—and geologists as well—in mastering geology, is to really come to grips with the slow rates at which geological processes happen and the vast amount of time involved. The problem is that our lives are short and our memories are even shorter. Our experiences span only a few decades, so we really don't have a way of knowing what 11,700 years means. What's more, it's hard for us to understand how 11,700 years differs from 65.5 million years, or even from 1.8 billion years. It's not that we can't comprehend what the numbers mean—we can all get that figured out with a bit of practice—but even if we do know the numerical meaning of 65.5 Ma, we can't really appreciate how long ago it was.

You may be wondering why it's so important to really "understand" geological time. One key reason is to fully appreciate how geological processes that seem impossibly slow can produce anything of consequence. For example, the slow movement of tectonic plates that over geological time can travel many thousands of kilometres!

One way to wrap your mind around geological time is to put it into the perspective of single year, as we did in Table I1 the introductory chapter, because we all know how long it is from one birthday to the next. At that rate, each hour of the year is equivalent to approximately 500,000 years, and each day is equivalent to 12.5 million years. It's worth repeating: on this time scale, the earliest ancestors of the animals and plants with which we are familiar did not appear on Earth until mid-November, the dinosaurs disappeared after Christmas, and most of Canada was periodically locked in ice from 6:30 to 11:59 p.m. on New Year's Eve. As for people, the first to inhabit Alberta got here about one minute before midnight, and the first Europeans arrived about two seconds before midnight.

## Media Attributions

- Figure 7.0.1: © Steven Earle. CC BY.

# Lab 7 Exercises

Figure A represents two road cuts, or cliff faces, exposed along a road way. You can see that at first glance, the road cuts look almost identical as they both expose the same four types of rock: granite, sandstone, limestone, and shale.

1. As a quick review from Labs 4, 5, and 6, how did each of these rocks form? Briefly summarize the origin of each rock in the table below.

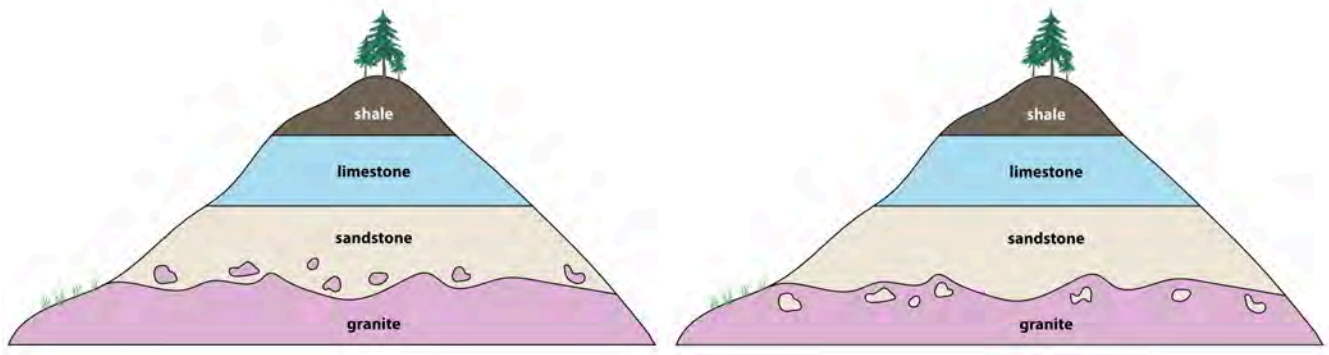



*Figure A*

| Rock Type | Granite | Sandstone | Limestone | Shale |
|---|---|---|---|---|
| **Origin** | | | | |

2. Examine the two road cuts carefully, and using the principles of stratigraphy, write a point-form **geologic history** for each road cut. A geologic history is a written sequence of events that describes what geological processes happened in the past to produce the stratigraphy in a given area, like a timeline. Your geologic history should use proper terms to describe each event. For example, we would say that a sedimentary rock was deposited and then lithified. We would not say that a sedimentary rock "intruded" or "erupted" because these terms are reserved for intrusive and extrusive igneous rocks, respectively. If there are any unconformities present, identify which type (review Figure 7.2.6) and briefly describe what the unconformity represents. This might include: a period of uplift and erosion, a period of non-deposition, or both.

| Youngest Event | Road Cut A (left) | Road Cut B (right) |
|---|---|---|
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| **Oldest Event** | • | • |

3. Do the two road cuts share the same geologic history? Why or why not?

4. Which key principle of stratigraphy helped you determine the difference between the two road cuts?

Road cuts and naturally-occurring cliffs provide us with a view into the subsurface to help us understand the nature of the layers of rock beneath our feet. Another way to visualize the subsurface is using a block diagram, or **block model** (Figure B). The top of the diagram shows the plan view, or map view, of the Earth's surface. The sides of the diagram show two different cross-sectional views down into the subsurface. These vertical cross-sections illustrate the geology below the surface.

We can see in Figure B, for example, that at the surface there is an active volcano (venting steam) that is connected at depth to a shallow magma chamber (E). The letters shown in this diagram, and in all the figures in this lab, are randomly assigned. In Figure B, layers G, H, J, and K are all sedimentary. Units B, C, D, E, L, and M are igneous.

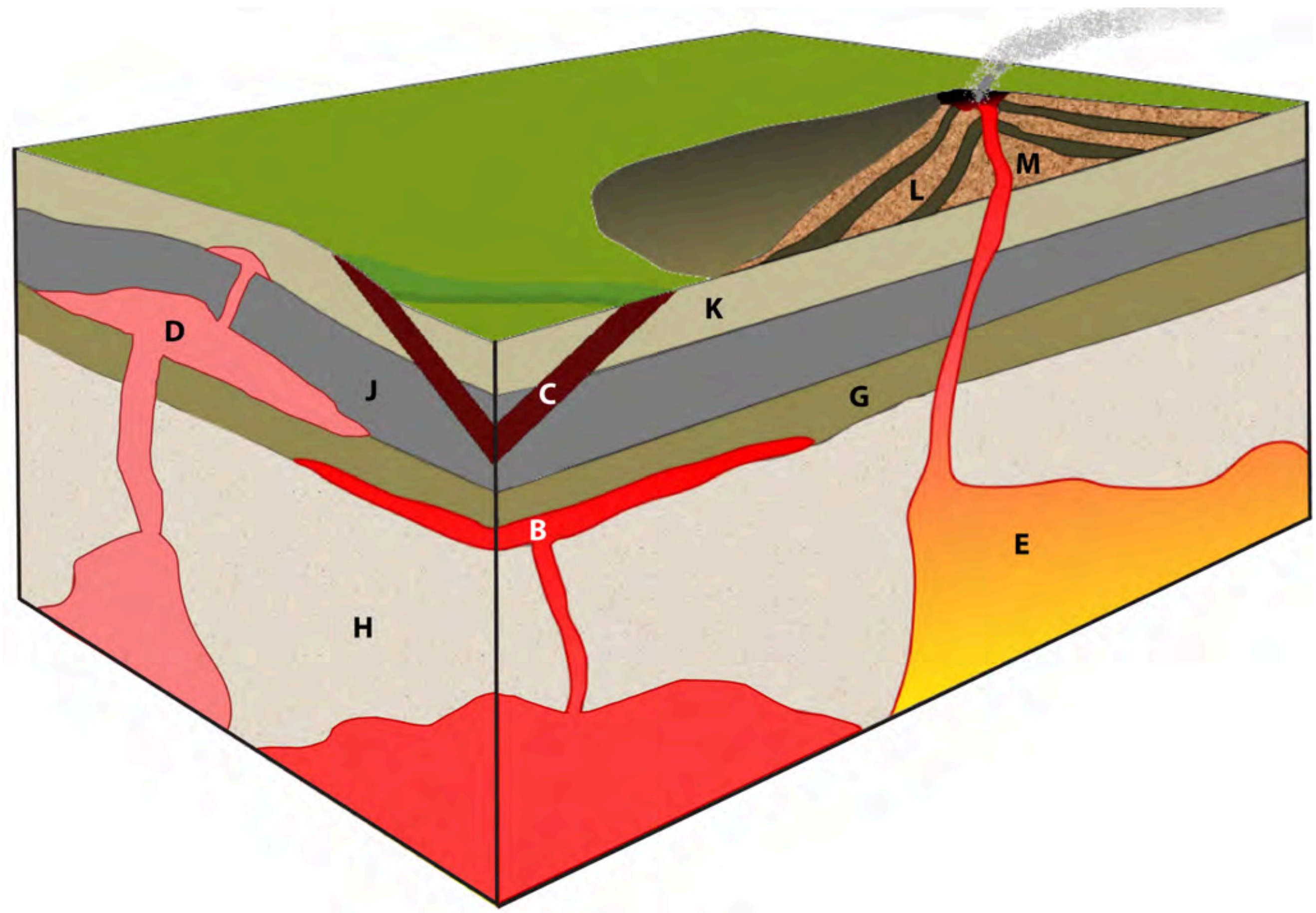



*Figure B*

5. Write a point-form geologic history for Figure B in the table below. Specify which stratigraphic principle(s) you used to justify the position of each event in the timeline.

| Youngest Event | Geologic History of Figure B | **Justification** (which principle of stratigraphy did you use?) |
|---|---|---|
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| **Oldest Event** | • | • |

6. Write a point-form geologic history for Figure C in the table below. Specify which stratigraphic principle(s) you used to justify the position of each event in the timeline. If there are any unconformities present, identify which type and briefly describe what the unconformity represents. This might include: a period of uplift and erosion, a period of non-deposition, or both. All the units in Figure C are sedimentary rocks, except B which represents an erosional surface.

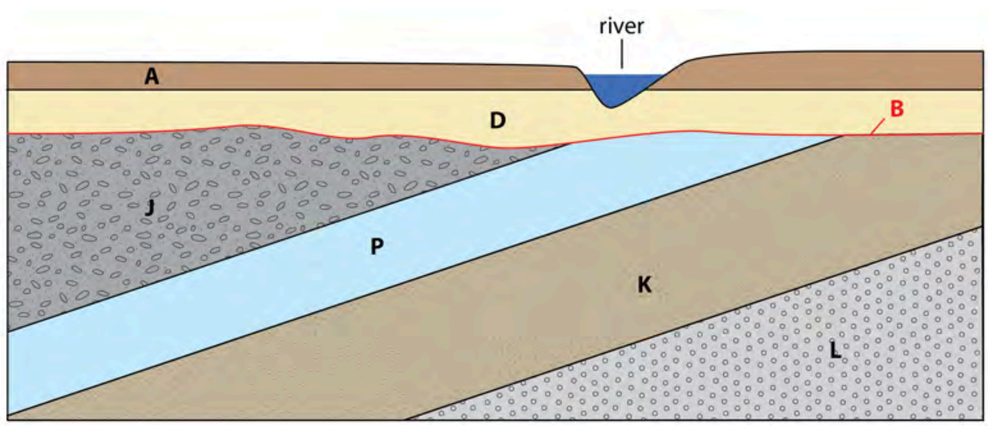



*Figure C*

| Youngest Event | Geologic History of Figure C | Justification |
|---|---|---|
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| Oldest Event | • | • |

7. In the space below, write a short paragraph (<150 words) describing the geologic history for Figure D using complete sentences. To describe the sequence of sedimentary rocks, you may want to use the term "overlain", as in "the Pennsylvanian conglomerate is overlain by the Permian shale", or as an adjective, "the overlying Permian shale". Unit D is a basalt dyke (a type of igneous intrusion), and the line labeled as F is a **fault**. Read more about faulting in section 10.3.

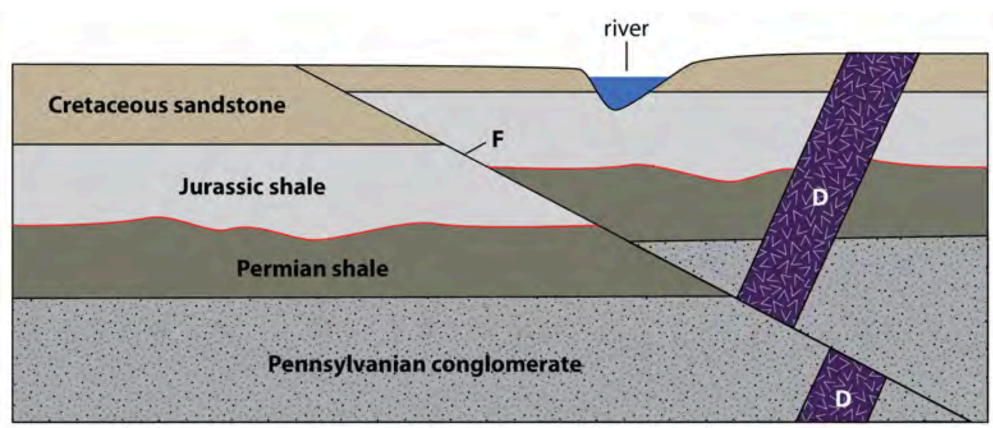



*Figure D*

8. Write a point-form geologic history for Figure E in the table below. Specify which stratigraphic principle(s) you used to justify the position of each event in the timeline. Unit J is a granite pluton and sill (two types of igneous intrusion), and the line labeled as F is a **fault**. Read more about faulting in section 10.3.

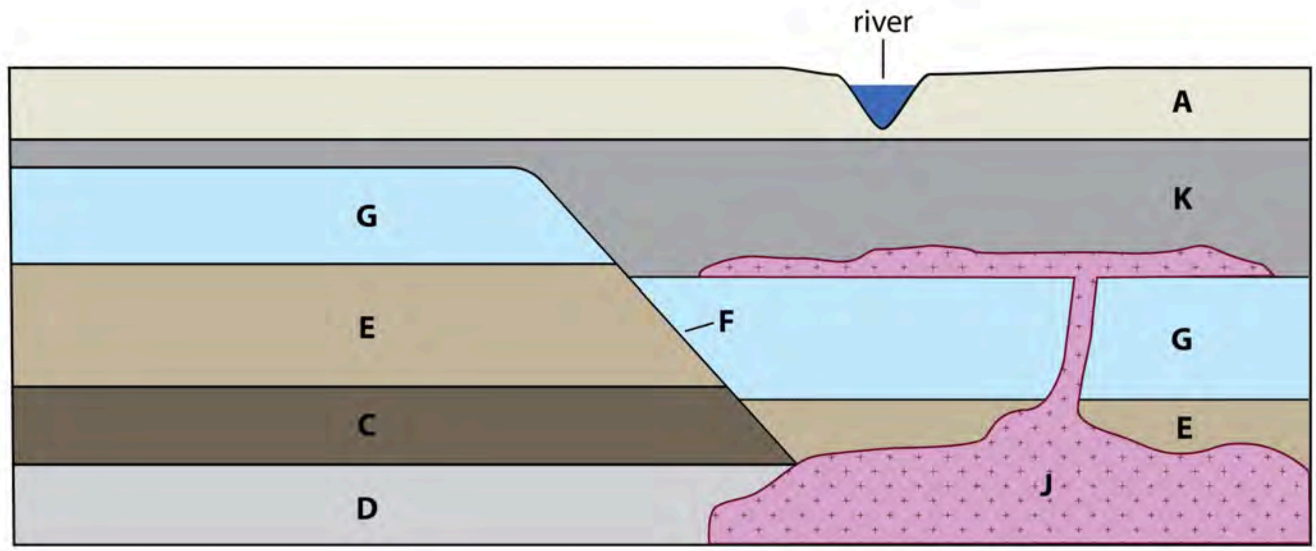



*Figure E*

| Youngest Event | Geologic History of Figure E | Justification |
|---|---|---|
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| Oldest Event | • | • |

9. Write a point-form geologic history for Figure F in the table below. Specify which stratigraphic principle(s) you used to justify the position of each event in the timeline. If there are any unconformities present, identify which type and briefly describe what the unconformity represents. Unit L represents a rhyolite dome formed by felsic lava. Letter A refers to the surface denoted by the red line. Letter F represents a fault plane. All other letters refer to sedimentary rocks. Note that units B, C, and D have been folded into **anticlines** and **synclines**. Read more about folds in section 10.2.

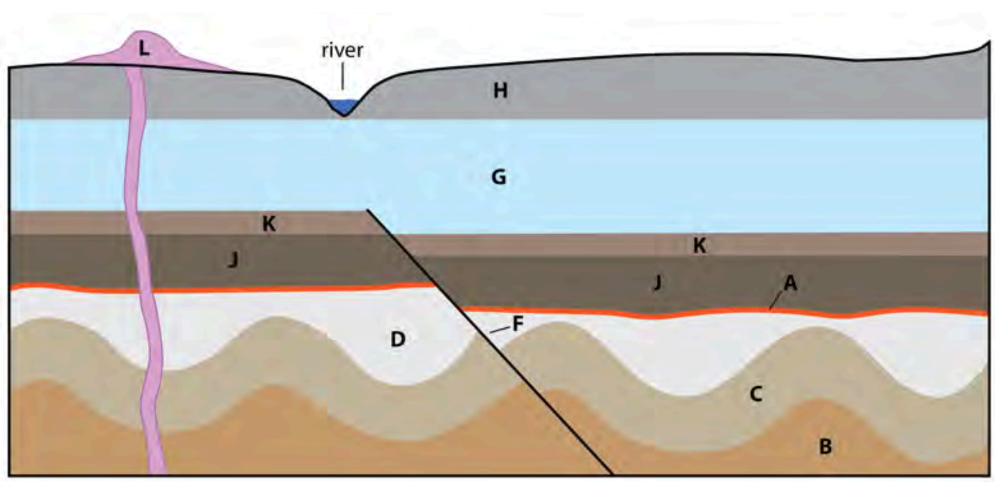



*Figure F*

| Youngest Event | Geologic History of Figure F | Justification |
|---|---|---|
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| | • | • |
| **Oldest Event** | • | • |

## Media Attributions

- Figures A, C, D, E, F: © Siobhan McGoldrick. CC BY.
- Figure B: © Siobhan McGoldrick. Adapted after Figure 3.5.2 © Steven Earle. CC BY.

# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 7.1 The Geological Time Scale | The work of William Smith was critical to the establishment of the first geological time scale early in the 19th century, but it wasn't until the 20th century that geologists were able to assign reliable dates to the various time periods. Geological time is divided into eons, eras, periods, and epochs and the geological time scale is maintained and updated by the International Commission on Stratigraphy. |
| 7.2 Relative Dating Methods | We can determine the relative ages of different rocks by observing and interpreting relationships among them, and applying the principles of stratigraphy. Gaps in the geological record are represented by various types of unconformities. |
| Lab 7 Exercises | The principles of stratigraphy can be applied to determine the geologic history of an area. Road cuts, cliff faces, and cross-sections give us an excellent insight into the geology of the subsurface, and the sequence of geologic events responsible for the strata observed can be solved like a puzzle. Keep in mind, that these stratigraphic principles can also be applied to relationships displayed in any outcrop, hand sample, and even in thin section! For example, using the principle of inclusions: a microscopic fluid inclusion within a crystal of quartz must be older than the quartz itself. |

# LAB 8: MAPPING FLUVIAL LANDSCAPES

## Lab Structure

| | |
|---|---|
| Assignment | Yes – submit fluvial features map |
| Recommended additional work | Yes – Practice Exercise 8.3 |
| Required materials | Tracing paper, pencil, pencil crayons, ruler, printed Elbow River Map Area base image |

*Learning Objectives*

After reading the background information in this chapter, and completing the exercises within it, you should be able to:

- Understand and interpret maps as a geologist.
- Identify erosional and depositional features associated with fluvial environments.
- Describe the evolution of a meandering stream.
- Locate topographic maps within Canada using the National Topographic System (NTS).
- Describe locations using UTM coordinates.
- Understand map scale and how to determine distances on a map.
- Understand how elevation data are presented on a topographic map as contour lines.
- Create a surficial geology map of fluvial features.

## Key Terms

- Meandering stream
- Braided stream
- Stream gradient
- Stream channel
- Flood plain
- Discharge
- Erosion
- Deposition
- Cut bank
- Point bar
- Oxbow lake
- Meander scar
- Scroll bar
- Delta
- Levée
- Legend
- Map scale
- UTM coordinates
- National Topographic System (NTS)
- Topographic contour lines
- Contour interval

Streams are the most important agents of erosion and transportation of sediments on Earth's surface. They are responsible for the creation of much of the topography that we see around us. They are also places of great beauty and tranquility, and of course, they provide much of the water that is essential to our existence. But streams are not always peaceful and soothing. During large storms and rapid snowmelts, they can become raging torrents capable of moving cars and houses and destroying roads and bridges. When they spill over their banks, they can flood huge areas, devastating populations and infrastructure. Over the past century, many of the most damaging natural disasters in Canada have been floods, and we can expect them to become even more severe in the near future as the climate changes.

Canada's most costly flood ever was the June 2013 flood in southern Alberta, affecting the communities of Canmore, Calgary, Okotoks, and High River (Figure 8.0.1). The flooding was initiated by snowmelt and worsened by heavy rains in the Rockies due to an anomalous flow of moist air from the Pacific and the Caribbean. At Canmore, rainfall amounts exceeded 200 millimetres in 36 hours, and at High River, 325 millimetres of rain fell in 48 hours.

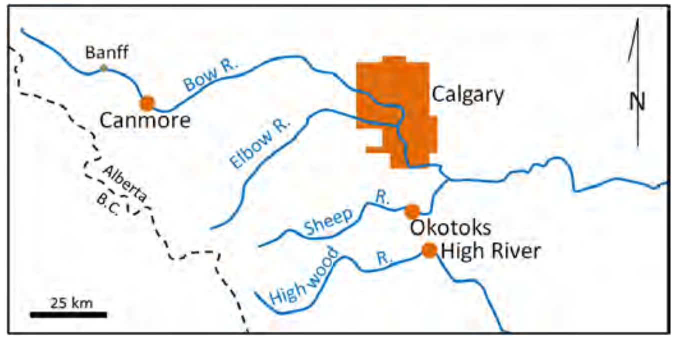


*Figure 8.0.1: Map of the communities most affected by the 2013 Alberta floods (in orange).*

In late June and early July, the discharges of several rivers in the area, including the Bow River in Banff, Canmore, and Exshaw, the Bow and Elbow Rivers in Calgary, the Sheep River in Okotoks, and the Highwood River in High River, reached levels that were 5 to 10 times higher than normal for the time of year! Large areas of Calgary, Okotoks, and High River were flooded and five people died. The cost of the 2013 flood is estimated to be approximately $5 billion.

One of the things that the 2013 flood on the Bow River teaches us is that we cannot predict when a flood will occur or how big it will be, so in order to minimize damage and casualties we need to be prepared. Some of the ways of doing that are as follows:

- **Mapping flood plains** and not building within them
- Building dykes or dams where necessary
- Monitoring the winter snowpack, the weather, and stream discharges
- Creating emergency plans
- Educating the public

## Media Attributions

- Figure 8.0.1: © Steven Earle. CC BY.
- Elbow River Map Area satellite image used under the following Google Maps and Google Earth guidelines.

# Lab 8 Exercises

In this activity you will learn to identify features of a stream using satellite imagery in Google Earth Pro. You will create a hand-drawn map of the fluvial features you identify along a segment of the Elbow River in Calgary, Alberta on the homelands of the Niitsitapi (the Siksika, Piikani, and Kainai), the Îyârhe Nakoda and Tsuut'ina Nations. Located just south of Mount Royal University's campus, this segment of the Elbow River was one of the areas affected by the 2013 flooding. Elbow River also plays a crucial role in supplying Calgary's drinking water.

You have been provided with the following starting materials to complete this mapping activity:

- A base image from Google Earth satellite imagery (Elbow River Map Area) that you must print out
- A digital copy of the 082J-16 NTS Priddis map sheet on which your map area resides (do not print this)

The purpose of your map is to show your reader the locations of erosional and depositional features of the Elbow River. To convey that information in a way that is useful, your map needs to include some standard **cartographic elements** including:

- Title
- Scale
- North arrow
- Legend
- Sources (e.g., satellite imagery, base map, reference map)
- UTM coordinates for a reference point on your map
- Refrence to the National Topographic System (NTS) map sheet on which your map resides

## Title

Your map should have a succinct but descriptive title that includes some reference to the geographic area. This could include the name of the river, the NTS map sheet on which your map resides, or the name of a prominent local landmark that is featured on your map. Your title must also include what type of map you have drawn, e.g., topographic map, geological map, map of glacial landforms, map of population distributions, etc.

## Scale

Your map must indicate scale using both a scale bar and a representative fraction. Remember, you can calculate the scale on your map by comparing the length of a distinctive feature on your map and a topographic map of the same area. But first, because you are examining an electronic version of the topographic map on a computer screen rather than a printed version you need to ensure that you are viewing the topographic map at the correct scale (as your device may distort the size of the image on the screen).

To check if your topographic map PDF is being displayed correctly, measure the scale bar on the map. For a 1:50,000 map sheet like the one you are using, 1 cm on the scale bar should represent 500 m on the ground. By holding up a ruler to measure, zoom in and out until this is true on your computer screen before you follow the steps below.

1. Measure a feature that is visible and distinctive on both your map and the topographic map. Record your measurements in the same units for both. The distance between intersections along a road, or in a straight line between two distinctive features are good places to measure.
2. Use the formula below:

$$Your\ map\ scale = \frac{(length\ of\ the\ feature\ on\ topographic\ map)\ x\ (map\ scale)}{length\ of\ the\ feature\ on\ your\ map}$$

For example, for a feature 5 cm long on your map and 2.5 cm-long on the 1:50,000 topographic map:

$$Your\ map\ scale = \frac{(2.5\ cm)\ x\ (50{,}000)}{5\ cm} = 1{:}\ 25{,}000$$

The scale of the base image in this example is therefore 1:25,000. This result is not particularly realistic as air photo or satellite imagery scales rarely work out to such a nice, even number.

## North arrow

Exactly as it sounds: a north arrow on a map shows the reader the direction of north in the area.

## Legend

The purpose of a legend is to define all symbols, abbreviations or colours used on a map to the reader. Every feature that you draw or label on your map should be explained or defined in the legend. For example:

| **Abbreviation or symbol on the map** | **Meaning** |
|---|---|
| Fp | Flood plain |
| Ms<br>—–- | Meander scar<br>Trail |

Feel free to create your own abbreviations or symbols for features on your map, but make sure you choose unique abbreviations or symbols for each feature.

## Reference location

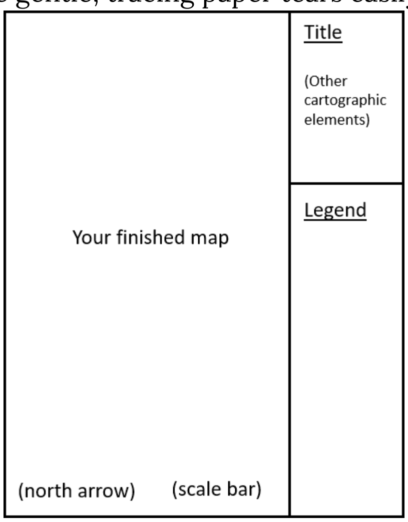
To help your reader put the information from your map into a real-world context, you should provide the UTM coordinates for a reference location on your map. You may want to refresh your memory on grid coordinates by reviewing the Google Earth Tutorial. This location should be something visible and distinctive on both your map and the topographic map provided. Furthermore, this location should be a feature that is unlikely to move over time, e.g., a point bar would be a poor choice as the shape and position of the point bar migrates over time. You will also need to tell your reader where your mapped area fits into Canada's National Topographic System (NTS).

## Instructions

1. Examine the area you will be mapping (Elbow River Map Area).

2. Open Google Earth Pro on your computer and navigate to this area. Spend some time examining the features of this area using the 3D capabilities of Google Earth Pro.

3. Attach a piece of tracing paper to your printed satellite imagery with a paper clip or piece of clear tape. Be gentle; tracing paper tears easily! Be very careful when erasing!




4. Set up your map area. Make sure that you have enough space on your tracing paper set aside for your legend and other cartographic elements (see checklist below). The example shown here illustrates one possible layout, but feel free to choose a layout that works with your map area.

5. With a pencil, lightly and neatly draw in the major landforms that you see in the satellite imagery. Focus on fairly large-scale structures; don't clutter up your map with a lot of detail. Think about what features are relevant to the fluvial features map you are drawing, and then make a judgement call for yourself about what features to include. For example, is it important to your map to draw in every building? Or to highlight areas with different types of vegetation? Probably not. But is it important to have a few key roads on your map to help a reader situate your map? Yes, it is.

6. Think about neatness. Examine the topographic map provided. What characteristics make it neat and easy to read? It is drawn carefully and the features are not shaded in. Remember: you are producing a map, which is drawn in plan view. It should not have any 3D aspect to it, including shading. Your finished product should be a line drawing only.

7. Use the topographic map provided to help you identify named geographic features.

8. Trace out the different fluvial features that you have interpreted, and assign each feature a unique abbreviation or symbol. Keep track of the abbreviations or symbols that you use on a spare sheet of paper to help format your legend once you have finished your map.

9. If the feature you are tracing is a polygon (an enclosed area that defines the borders of the specific feature), make sure your polygon is fully closed and labeled with an abbreviation, symbol or colour. Make sure every polygon you draw is labeled.

10. Review the checklist below and ensure that your finished map contains all the required information.

| **Fluvial Features** | **Cultural Features** | **Cartographic Elements** |
|---|---|---|
| Active channel | Roads | Title |
| Cut bank | Bridges | North arrow |
| Point bar | Buildings or subdivisions | Scale bar |
| Abandoned channel | | Scale as representative fraction |
| Oxbow lake | | Legend |
| Delta | | Reference to NTS sheet on which this map resides |
| Flood plain | | Reference point in UTM coordinates |
| Meander scar | | Elevation of reference point in metres (estimate using the topographic contours) |
| | | Date of satellite imagery and source of satellite imagery |
| | | Author's name (your name) |

## Summary Questions

1. What is the National Topographic Index Number for the topographic map provided? ___________
2. What is the National Topographic Index Number for the topographic map directly to the north of this map? ___________
3. What colour are grid lines for UTM Zone 11 on the topographic map sheet provided? ___________
4. What colour are the topographic contour lines on the topographic map sheet provided? ___________
5. What is the contour interval (C.I.) on this topographic map? ___________
6. Examine the spacing between adjacent contour lines on the topographic map provided. In what general part of the map do you see relatively steep topography? In what general part of the map do you see relatively gentle topography? How can you tell the difference using the contour lines?

---

7. Draw a sketch of a few contour lines, with elevations labeled, as they cross a stream. On your sketch, indicate the direction of stream flow with an arrow.
8. Where would you expect to find the fastest water flow on a straight stretch of a stream? _______________ ______________________________
9. Sand grains can be moved by traction and saltation. What minimum stream velocities might be required to move 1 millimetre sand grains? _____________
10. Under what circumstances might a braided stream develop?

---

11. What do you think controls the variability in the colour of the water in Glenmore Reservoir in this satellite image?

---

12. What factors or forces influence the behaviour of the Elbow River? Hint: Examine the most recent satellite imagery for your map area in Google Earth Pro.

---

---

If you have the opportunity to do so, and provincial health authorities deem it safe, you are encouraged to safely and respectfully visit this area, called Weaselhead Flats, yourself. Walk around the Weaselhead Flats and see what fluvial features you can identify in person. Grab a handful of sediment from a point bar and examine the size, shape and composition of the grains. As for any field work, always:

- Stay on the trails, be mindful of other trail users and maintain 2 m of physical distancing.
- Dress appropriately for changing weather conditions. Think layers!
- Bring water, a hat and sunscreen.
- Wear appropriate footwear that covers your foot completely, provides some ankle support, and has a good tread in case the path is slippery.
- If you are exploring along the river bank, walk cautiously and be mindful of loose soil or sediment that may collapse.
- Make a plan! Make sure you tell someone when you are expected home and check in with them once you return.

## Media Attributions

- Elbow River Map Area and Glenmore Reservoir and area satellite images used under the following Google Maps and Google Earth guidelines.
- 082J-16 NTS Priddis topographic map: © Natural Resources Canada. The Government of Canada retains the copyright of this image but allows for reproduction for non-commercial use.
- Example map layout: © Siobhan McGoldrick. CC BY.

# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 8.1 Stream Erosion and Deposition | Erosion and deposition of particles within streams is primarily determined by the velocity of the water. Erosion and deposition of different-sized particles can happen at the same time. Some particles are moved along the bottom of a river while some are suspended in the water. It takes a greater velocity of water to erode a particle from a stream bed than it does to keep it in suspension. Ions are also transported in solution. When a stream rises and then occupies its flood plain, the velocity slows and natural levées form along the edges of the channel. |
| 8.2 Stream Types | Youthful streams in steep areas erode rapidly, and they tend to have steep, rocky, and relatively straight channels. Where sediment-rich streams empty into areas with lower gradients, braided streams can form. In areas with even lower gradients, and where silt and sand are the dominant sediments, meanders are common. Deltas form where streams flow into standing water. |
| 8.3 What Makes a Map? | Maps are used to share spatial data, and geologists often create maps using a topographic base map. All maps contain standard cartographic elements such as a title, scale, north arrow, legend, and other ancillary information that helps the reader understand the map. Topographic maps in Canada are indexed in the National Topographic System. Contour lines are drawn to show relief of the landscape on a topographic map. |
| Lab 8 Exercises | The best way to learn about important cartographic elements and mapping is to make a map yourself! Fluvial features along a meandering segment of the Elbow River in Calgary, Alberta can be identified and mapped based on satellite imagery. A good map conveys information about your interpretations to your reader. Adding a reference point with a UTM coordinate and a reference to the NTS map sheet on which your map resides helps your reader situate your interpretations in a larger context. |

# LAB 9: STRUCTURAL GEOLOGY PART I

## Lab Structure

| | |
|---|---|
| Assignment | Yes – take-home mapping assignment |
| Required materials | Tracing paper, pencil, pencil crayons, ruler, printed Sheep Mountain map area base image |

*Learning Objectives*

After reading the information in this chapter, and completing the exercises within it, you should be able to:

- Visualize topographic contours in Google Earth and review the concepts of topographic maps presented in Lab 8.
- Visualize layers of rocks as planes in three-dimensional space, in areas of variable topography.
- Recognize and describe different units of rock in satellite imagery and on geological maps.
- Understand the significance of the information presented on a geological map.
- Understand the concept of dip and dip direction of inclined strata.
- Use the three-dimensional capabilities of Google Earth Pro to identify dip direction of inclined strata.
- Estimate dip direction of inclined strata in map view using the Rule of V's.

## Key Terms

- Strata
- Planar
- Contact
- Cardinal direction
- Ordinal direction
- Contour lines
- Dip
- Dip direction
- Lithology
- Unit
- Map scale
- Formation
- Group
- Member
- Bed
- Rule of V's

# Lab 9 Exercises

Today, you will be learning the basic principles of geological mapping. In this activity you will learn to identify layers of rock, group them into mappable layers, and identify dip direction using satellite imagery in Google Earth Pro. The take-home assignment you will complete aims to link together all the topics covered in this lab to introduce you to geological mapping using satellite imagery.

Before you get started, download Google Earth Pro (free) for desktop. Web or Mobile versions are also available but they do not have all the features you will be required to use in this activity.

## Instructions

Download the 1101 Lab 9.kmz file provided by your instructor. In Google Earth Pro, click *File*, *Open* and navigate to wherever you saved the downloaded .kmz file.

In the left panel you should see a list of places in this kmz file, double click on "Raplee Anticline". We will begin by examining the Google Earth satellite imagery only, so uncheck the box next to "Mexican Hat Topographic Map".

1. Examine the area around Raplee Anticline from an altitude of ~5 km. Write down any observations you have about this area.

2. Notice the different colours. What might these different colours represent?

3. Why are we examining this area to study bedrock geology? Why not look around Calgary? Why not look around Vancouver, BC?

Turn on the "Mexican Hat Topographic Map" layer by checking the box next to it in the Places sidebar. Make sure the map is 100% opaque (not transparent at all).

- To adjust the transparency, right click on the name of the layer in the Places sidebar, and select Properties.
- A dialogue box should appear. Click and drag the bar to adjust the transparency of the topographic map overlay.

Now that you are examining a topographic map draped over the 3D landscape in Google Earth, let's review some concepts about topographic maps from Lab 8.

4. What units are used to show elevation on this topographic map?

5. What is the contour interval on this topographic map?

6. What do topographic contour lines do when they cross a stream? If you're not sure, examine one of the streams to the northwest of the Raplee Anticline, but still on the east side of the San Juan River.

Adjust the transparency of the topographic map such that it is almost transparent but the topographic contour lines are still visible.

7. Examine the immediate area around the Raplee Anticline in plan view (remember, you can press r on your keyboard to return to plan view). What do you notice about the contour lines relative to the contacts? Hint: the contacts are the planes between layers of rocks of different colours.

8. Rotate the view to examine the area in 3D. Circle the correct answer: do these layers in the immediate area around Raplee Anticline appear to be horizontal, vertical, or dipping?

9. If you were to walk 500 m from Raplee Anticline, heading due west, would you be walking over progressively younger or older rocks? What principle of stratigraphy did you use to determine this?

10. Examine the strata directly to the west of Raplee Anticline but still on the east side of the San Juan River. Again, compare the strata that you can recognize by the variations in colour to the contour lines. Do these strata appear to be horizontal as well? Why or why not?

11. Rotate the view until you are looking directly east toward Raplee Anticline. Look closely at the jagged-looking layers of red and grey rocks. Notice how if you try to trace a single layer of rock it makes a jagged line? That is because these layers are dipping. Rotate your view to see this in 3D and confirm these layers are indeed tilted, or using proper terminology, they are dipping.

Let's practice using the **Rule of V's** to determine the **dip direction** of these strata. To make this easier, turn off the topographic map by unchecking the box.

- Take another look at one of the streams you examined earlier, just to the NW of Raplee Anticline.
- Zoom in, press r to return to plan view, and pick a distinctive stratum (a single layer of rock) to trace.

- Trace your chosen stratum across this stream. Notice how it makes a "V" shape and the point of the "V" points in the direction of dip.

12. What is the dip direction of these dipping strata? Remember, think of dip direction as the direction water would flow if poured onto the layer of rock.

---

So far, you have seen that dry, arid climates make excellent areas for virtual field work because there is little vegetation to obscure your view of the geology! You have observed that different rock units may be distinguished even in satellite imagery based on colour differences. You have seen how horizontal strata have contacts that are parallel to topographic contour lines, and how dipping strata have contacts that deflect across contour lines. You have also practiced using the Rule of V's to determine dip direction.

Let's explore a couple more arid regions of the world with spectacular geology: Karkh, Pakistan and Dekhuyeh, Iran.

13. Use the Rule of V's to determine the dip direction of the light beige coloured layers of rock near Karkh, Pakistan.

14. Use the Rule of V's to determine the dip direction of the light beige coloured layers of rock near Dekhuyeh, Iran.

Finally, let's explore one more field area to relate the geology you can see in Google Earth to a geological map. Navigate to "Sheep Canyon Area" and examine this area from an altitude of ~9 km. Notice how you can see the different layers clearly because this area has very little overburden and vegetation to hide the bedrock geology. Turn on the "Sheep Canyon Geological Map" layer. Toggle the layer on and off, or adjust the transparency.

15. How are the rocks of different colours that you could see in the satellite imagery depicted on the geological map?

---

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In Lab 8 you created a fluvial surficial geology map – a map of sediment deposited by a river. That is one type of map used in geology, to show deposits of loose sediment on the Earth's surface. Another type of geological map shows the bedrock, meaning the layers of hard, fully-lithified rocks that are exposed at the Earth's surface. All the layers of rock you have been studying today are examples of bedrock.

Rocks are typically mapped in packages that are often formally named **formations** or **groups**. Notice how each formation on the Sheep Canyon geological map has a map code associated with it to link each formation to the legend.

16. Can you see anywhere on this map or in the Google Earth satellite imagery where you could use the Rule of V's to determine dip direction? For which unit could you do this? State the complete formation name, the map code, and the dip direction.

---

---

Now that you have a sense of how to visualize layers of rocks in three-dimensions, and what the different colours on a geological map represent, we are going to focus in on how to read geological maps. Close

Google Earth Pro, and open the digital PDF copy Sheep Canyon Geological Map to answer the following questions.

17. What is the full title of this map?

18. Who is the author of this map?

19. What is the scale of this map?

20. What is the distance in kilometers measured along Highway 14-16-20 from the intersection with Highway 310 to the intersection with the pipeline?

21. What information is provided for each mapped unit in the legend of a geological map?

22. In what order are the formations listed in the legend?

23. What is the map code, name, age, and lithology of the oldest unit on this map?

24. In what general area of the map would you find this unit exposed at the surface?

25. What is the map code, name, age, and lithology of the youngest formation on this map?

26. In what general area of the map would you find this formation exposed at the surface?

27. What are the full names of the two formations deposited during the Pennsylvanian? Which of the two is oldest?

28. If you were going to start a drywall manufacturing business, which formation(s) would you be most interested in exploring?

## Media Attributions

- 1101 Lab 9.kmz file by Siobhan McGoldrick. Derivative of Kmz file of placemarks for other structural mapping examples by Barbara Tewksbury, Locations in Google Earth for teaching geologic mapping and map interpretation, used under CC-BY-NC-SA 3.0.
- Mexican Hat Topographic Map © USGS. Public domain.
- Sheep Canyon Geological Map by Robert E. Ladd © Wyoming State Geological Survey. All rights reserved. Used with permission.

# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 9.1 Introduction to Structural Geology | Visualizing layers of rocks as 3D forms is a fundamental skill for any geologist. Layers of rocks often form as planes, and the attitude of any plane can be described by specifying its dip and dip direction. Dip is the angle between 0° (horizontal) and 90° (vertical) measured from horizontal to the inclined plane. Dip direction refers to the direction of maximum dip, or the direction towards which water would flow if it was poured onto the dipping plane. In this course, we will use cardinal (e.g., W for west) and ordinal directions (e.g., SE for southeast) to describe dip direction. |
| 9.2 Geological Maps | Geological maps share many common cartographic elements with topographic maps. The legend on a geological map displays information about each unit, including map code, full unit name (e.g., formation name), age, and a brief description of lithology. Legends are formatted such that the oldest rocks are listed at the bottom, and the youngest rocks at the top. Map patterns of units on a geological map reflect the intersection of geology (i.e., the attitude of the strata) and topography. |
| 9.3 Estimating Dip Direction from a Geological Map | Determining the dip direction in a block model, where the top surface is perfectly flat, is straightforward. In real life, topography influences the map pattern of a unit. Some clues in map view can help estimate the dip and dip direction of strata: horizontal strata have contacts that are parallel to topographic contour lines, and vertical strata have contacts that appear to cut across contour lines at a high angle. For dipping units, the Rule of V's provides a quick, visual method of estimating the dip direction by examining how a dipping contact is deflected across a stream or valley in map view. |
| Lab 9 Exercises | Satellite imagery of areas with arid climates is often clear enough to distinguish different layers of bedrock where they are exposed at the Earth's surface. In the same way that we can group together and map layers of rocks seen in satellite imagery based on common visible features (i.e., colour), geologists group together mappable units of rock to create a geological map. In arid areas where exposure of the bedrock is extensive, and visible differences between units are distinct, map patterns and dip direction can be determined using satellite imagery and the Rule of V's. |

# TAKE-HOME MAPPING ASSIGNMENT

Complete Lab 9 before you attempt this assignment.

*Learning Objectives*

After completing this take-home activity, you should be able to:

- Draw a geological map from satellite imagery, including all required cartographic elements and symbols to indicate dip direction.

## Geological Map of Sheep Mountain

As a take-home assignment, create a hand-drawn geological map of the northern part of Sheep Mountain in Wyoming. This map area has been outlined in the 1101 Lab 9.kmz file for you to examine in Google Earth Pro, and is located on the homelands of Arapaho, Arikara, Bannock, Blackfoot, Cheyenne, Crow, Gros Ventre, Kiowa, Nez Perce, Sheep Eater, Sioux, Shoshone and Ute tribes. Sheep Mountain was selected for this activity because of the clear colour contrasts in the rocks, and because this area has very little vegetation to obscure your view of the rocks. Both of these features make it possible for you to actually map the bedrock geology based solely on satellite imagery.

The purpose of your geological map is to show your reader where different geologic units are exposed at the surface of the Earth. These units will be defined by you based on differences you observe in the satellite imagery.

### Instructions for creating your geological map

1. Examine the area you will be mapping (Sheep Mountain Map Area).

2. In Google Earth Pro you can navigate to this area, saved as a polygon called “Sheep Mountain Map Area” in the 1101 Lab 9.kmz file. Spend some time examining the features of this area using the 3D capabilities of Google Earth Pro.

3. Attach a piece of tracing paper to your printed satellite imagery with a paper clip or piece of clear tape. Be gentle; tracing paper tears easily! Be very careful when erasing!

4. Set up your map area. Make sure that you have enough space on your tracing paper set aside for your legend and other cartographic elements (review the checklist below). You may also format your legend on a separate piece of paper.

5. As you examine the base image and explore the map area in 3D using Google Earth Pro, decide how many different units you wish to include on your map. Remember, any geological map requires some degree of “lumping” (grouping together layers of rocks with something in common) or “splitting” (separating layers of rock into distinct units to be mapped separately). Your map must have at least four, distinct units. Think

about how you would briefly describe each of your units in the legend of your map. In this case because you are working only from an image and cannot reliably identify lithology, your description will likely focus on the colour of the rocks.

6. With a pencil, lightly and neatly draw in the contacts that you see between different units in the satellite imagery. The contacts (lines) that you draw around a particular area will delineate a polygon that contains a rock unit. Once you are confident with the contacts you have drawn, trace over them in black pen.

7. Colour in and write a map code inside each polygon. Keep track of the colours and map codes that you use on a spare sheet of paper to help format your legend once you have finished your map.

8. Review the checklist below and ensure that your finished map contains all the required information.

9. Scan OR take a clear photograph of your finished map to submit. It is your responsibility to ensure that your submission is legible. If your instructor cannot read your work, they cannot mark it!

10. Submit your finished map on Blackboard.

| **Geological Features** | **Geographic Features** | **Cartographic Elements** |
|---|---|---|
| At least four distinct units mapped and neatly coloured | Rivers or streams | Legend (includes the colour, map code, and a brief description of each of your units. Remember that the legend on a geological map always list the oldest unit at the bottom and the youngest unit on top! How can you determine which of your units is the oldest?) |
| Contacts between units drawn in black pen | Roads (if any) | North arrow |
| Black arrows to indicate dip direction on the NE and SW sides of the mountain | | Scale bar |
| | | Scale as representative fraction |
| | | Title |
| | | Reference point in UTM coordinates |
| | | Date of satellite imagery and source of satellite imagery |
| | | Author’s name (your name) |

## Media Attributions

- 1101 Lab 9.kmz file © Siobhan McGoldrick. CC-BY-NC-SA 4.0. Derivative of Kmz file of placemarks for other structural mapping examples © Barbara Tewksbury, Locations in Google Earth for teaching geologic mapping and map interpretation, used under CC-BY-NC-SA 3.0.
- Sheep Mountain Map Area satellite image used under the following Google Maps and Google Earth guidelines.

# LAB 10: STRUCTURAL GEOLOGY PART II

## Lab Structure

| | |
|---|---|
| Recommended additional work | Yes – review for final lab project |
| Required materials | Printed block models 1 to 6, pencil, pencil crayons, ruler, protractor |

*Learning Objectives*

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Describe the types of stresses that exist within the Earth's crust.
- Explain how rocks respond to those stresses by brittle, elastic, or plastic deformation, or by fracturing.
- Summarize how rocks become folded and know the terms used to describe the features of folds.
- Summarize the different types of faults, including normal, reverse, thrust, and strike-slip.
- Visualize layers of rocks that form complex geologic structures in three-dimensional space.
- Recognize and describe geologic structures in block models and on geological maps.
- Describe the geologic history of a structurally complex area.

## Key Terms

- Stress
- Strain
- Compression
- Tension
- Shear
- Ductile
- Brittle
- Deformation
- Anticline
- Syncline
- Limbs
- Axial plane
- Hinge zone
- Fracture
- Hanging wall
- Footwall
- Normal fault
- Reverse fault
- Strike-slip fault
- Left-lateral
- Right-lateral

Observing and understanding geological structures helps us to determine the kinds of stresses that have existed within Earth's crust in the past. This type of information is critical to our understanding of plate tectonics, earthquakes, the formation of mountains, metamorphism, and Earth resources. Some of the types of geological structures that are important to study include bedding planes, planes of foliation, dykes and sills, fractures, faults, and folds. Structural geologists make careful observations of the orientations of these structures and the amount and direction of offset along faults. Locating and mapping these structural features is important for safe engineering of infrastructure such as roads and housing. A good understanding of geological structures in the subsurface is also critical for mineral and petroleum exploration.

# Lab 10 Exercises

The ability to visualize strata in three-dimensions is a spatial skill that is fundamental to understanding geology in the real world. For some, this skill comes easily. Bur for others, spatial thinking and visualization can be difficult concepts, especially at first. Regardless of which category of student you fall into, while these skills may come more naturally to some, they can be taught and will improve with practice! To practice visualizing in three-dimensions, think about the difference between how an object looks from above (in plan view), and how a slice through that object would look (in cross-section).

*Spatial thinking and cross-sections*

Imagine an apple. How would the apple look in plan view?

Now imagine slicing the apple in half, along a straight line. If you pull the two halves apart to examine the internal structure of the apple, you are looking at a cross-section. The photographs below show how the apple looks in plan view (left), and in cross-section (right). The dashed white line is the line of cross-section, from X to Y.

For more practice, imagine and sketch what the cross-section of the following objects would be:

- an orange
- a lemon cut in half from end to end
- a round loaf of sourdough bread, cut into slices
- a pyramid with a square base, cut along a diagonal line from corner to corner

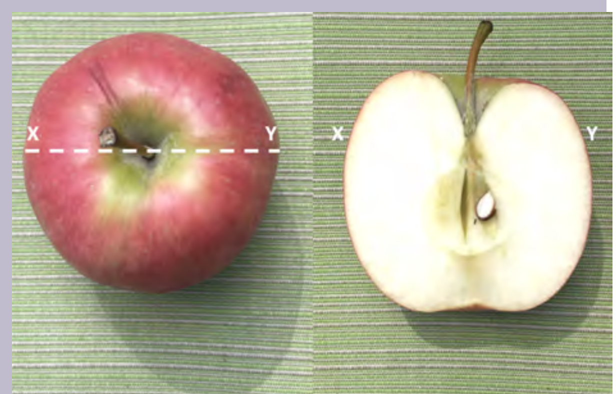


*Figure A*

Today you will use printed copies of the block models in Appendix 5 to explore geologic structures. Recall that the top surface of a block model represents the plan view of the Earth's surface, and the four sides represent four cross-sectional views down into the subsurface. On each of the six block models below, the geology drawn on the south- and west-facing sides shows the geology of the subsurface. This will give you some clues about the attitude (dip and dip direction) of the formations, as well as any structures present. Examine each of the block models, complete the missing sides, and use your completed model to answer the questions below. Unless otherwise stated, assume all the formations below represent sedimentary rocks.

For some of the models you will be asked to write a point-form geologic history based on what you observe in the model. This is an excellent way to review the relative dating and geologic time concepts from Lab 7. For example, try writing a point-form geologic history for Block Model 1 that shows a sequence of Cambrian (brown), Ordovician (light grey), Silurian (cream), Devonian (blue grey), and Mississippian (orange) formations that are dipping to the east, as well as a Cretaceous gabbro dyke (dark brown).

---

A point-form geologic history for Block Model 1 would look something like this:

**Youngest (most recent)**

- Erosion +/- uplift to present
- Intrusion of Cretaceous gabbro dyke (*cross-cutting relationships*)
- Tilting of the Cambrian to Mississippian formations toward the east (*original horizontality*)
- Deposition and lithification of the Mississippian formation (*superposition*)
- Deposition and lithification of the Devonian formation (*superposition*)
- Deposition and lithification of the Silurian formation (*superposition*)
- Deposition and lithification of the Ordovician formation (*superposition*)
- Deposition and lithification of the Cambrian formation (*superposition*)

**Oldest**

---

Notice how the history is formatted such that the oldest event is at the bottom, and the youngest or most recent event is listed at the top. The italic font in parentheses indicates the principle of stratigraphy used to justify the position of each event in the timeline. Also note that the terms used to describe the different geologic events match the type of rocks: **deposition** for sedimentary rocks, **intrusion** for the igneous dyke. Recall from Lab 3, that gabbro is a mafic intrusive igneous rock, that cooled beneath the Earth's surface. Since the gabbro dyke is now exposed at the surface of the Earth, the most recent event must be that the area has been uplifted and any overlying rocks or sediment have been eroded away.

## Block model 1

Cut out block model 1, then construct the model by folding along the red lines. Fold in the corners of the model to create a 3D rectangular shape. Do not staple or tape the corners yet, as the model is easier to complete when laid flat on a hard surface. Later, you may want to staple or tape these corners so that your model maintains its shape.

This model shows a sequence of Cambrian (brown), Ordovician (light grey), Silurian (cream), Devonian (blue grey), and Mississippian (orange) formations that are dipping to the east. A Cretaceous (dark brown) dyke is also shown.

1. Complete the north- and east-facing sides of the block by drawing in the geology. You do not need to colour in the block model, but your formations must be labeled.
2. Draw a black arrow in plan view to indicate the dip direction of the Ordovician formation (O) at point i.
3. Using your protractor, measure the dip of the Ordovician formation on the south-facing side of the block. Remember, dip is measured in degrees from horizontal (0°) down to the inclined plane. Review Figures 9.1.2 and 9.1.3 if you are unsure where the angle of dip should be measured on your block model. Dip:
4. Draw a black arrow in plan view to indicate the dip direction of the Cretaceous dyke (K) at point ii.
5. Using your protractor, measure the dip of the Cretaceous dyke on the south-facing side of the block. Dip:

## Block model 2

This model shows a sequence of Cambrian (brown), Ordovician (cream), Silurian (light grey), and Devonian (blue grey) formations. This model is a little more complex than Model 1, as the strata here have been folded.

1. Complete the north- and east-facing sides of the block by drawing in the geology. You do not need to colour in the block model, but your formations must be labeled.
2. Draw a black arrow in plan view to indicate the dip direction(s) of the Silurian formation (S) at points i, ii, and iii.
3. Draw on the axial plane for each fold in red pen on the south- and north-facing sides of the model.
4. In plan view and using a ruler, draw the surface traces of the axial planes for the folds in red pen. Add the appropriate symbols to indicate the type of fold (see Figure 10.2.5).
5. What type of stress is required to produce the geologic structures observed in this block model?

---

## Block model 3

This model shows a faulted sequence of Cambrian (green), Ordovician (blue), Silurian (grey), and Devonian (cream), and Mississippian (brown) formations. Examine the offset of the formations shown in the south-facing side of the block.

1. Complete the north- and east-facing sides of the block by drawing in the geology. You do not need to colour in the block model, but your formations must be labeled.
2. Draw a black arrow in plan view to indicate the dip direction of the Mississippian formation (M) at point i.
3. Draw a black arrow in plan view to indicate the dip direction of the fault at point ii.
4. Draw a black arrow in plan view to indicate the dip direction of the Silurian formation (S) at point iii.
5. Label the hanging wall and footwall on the south- and north-facing sides of the model (the blocks above and below the fault).
6. Draw red arrows on either side of the fault to indicate the sense of displacement along the fault.
7. Is the fault in this model a normal or reverse fault? Why?

---

8. Draw the appropriate map symbol for the fault in plan view. Consult Figure 10.3.4 for more information on map symbols for faults.
9. What type of stress is required to produce the fault observed in this block model?

---

## Block model 4

This model shows a faulted sequence of Cambrian (green), Ordovician (blue), Silurian (grey), and Devonian (cream), and Mississippian (brown) formations. Examine the offset of the formations shown in the south-facing side of the block.

1. Complete the north- and east-facing sides of the block by drawing in the geology. You do not need to colour in the block model, but your formations must be labeled.
2. Draw a black arrow in plan view to indicate the dip direction of the Mississippian formation (M) at point i.
3. Draw a black arrow in plan view to indicate the dip direction of the fault at point ii.
4. Draw a black arrow in plan view to indicate the dip direction of the Ordovician formation (O) at point iii.
5. Label the hanging wall and footwall on the south- and north-facing sides of the model (the blocks above and below the fault).
6. Draw red arrows on either side of the fault to indicate the sense of displacement along the fault.
7. Is the fault in this model a normal or reverse fault? Why?

---

8. Draw the appropriate map symbol for the fault in plan view. Consult Figure 10.3.4 for more information on map symbols for faults.
9. What type of stress is required to produce the fault observed in this block model?

---

## Block model 5

This model shows a faulted sequence of Cambrian (orange), Devonian (grey), and Mississippian (cream) formations, as well as a younger Cretaceous dyke (dark brown). Examine the offset of the dyke shown in the south-facing side of the block.

1. Complete the north- and east-facing sides of the block by drawing in the geology. You do not need to colour in the block model, but your formations must be labeled.
2. What is the dip of the Mississippian formation (M) at point i? Dip:
3. What is the dip and dip direction of the Cretaceous dyke (K) at point ii?

---

4. Draw red arrows on either side of the fault at point iii to indicate the sense of displacement along the fault.
5. What type of strike-slip fault is this? Why?

---

6. Write a point-form geologic history for this block model. Be sure to specify any unconformities (if present), and which principles of stratigraphy you use as evidence for your timeline.
7. What type of stress is required to produce the fault observed in this block model?

---

## Block model 6

This is a structurally-complex block model. This model shows a deformed sequence of Cambrian (brown), Ordovician (cream), Silurian (pale grey), and Devonian (blue grey) formations, as well as a Jurassic dyke (dark brown). The black unit on the south-facing side labeled 'M' is a Mississippian sill, a type of igneous intrusion.

1. Complete the north- and east-facing sides of the block by drawing in the geology. You do not need to colour in the block model, but your formations must be labeled.
2. What is the dip of the Silurian formation (S) at points i and ii? Indicate the dip direction in plan view at points i and ii by drawing black arrows.
3. Draw on the axial plane for the fold in red pen on the south- and north-facing sides of the model.
4. In plan view and using a ruler, draw the surface trace of the axial plane for the fold in red pen. Add the appropriate symbol to indicate the type of fold.
5. What is the dip and dip direction of the Jurassic dyke (J) at point iii?

---

6. What is the dip and dip direction of the fault at point iv?

---

7. Label the hanging wall and footwall on the east- and west-facing sides of the model.
8. Draw red arrows on either side of the fault to indicate the sense of displacement along the fault.
9. Is the fault in this model a normal or reverse fault? Why?

---

10. Write a point-form geologic history for this block model. Be sure to specify any unconformities (if present), and which principles of stratigraphy you use as evidence for your timeline.

## Media Attributions

# Summary

The topics covered in this chapter can be summarized as follows:

| Section | Summary |
|---|---|
| 10.1 Stress and Strain | Stress within rocks—which includes compression, extension and shearing—typically originates from plate-boundary processes. Rock that is stressed responds with either elastic or plastic strain, and may eventually break. The way a rock responds to stress depends on its composition and structure, the rate at which strain is applied, and also to the temperature of the rock body and the presence of water. |
| 10.2 Folding | Folding is generally a plastic response to compressive stress, although some brittle behaviour can happen during folding. An upward fold is an antiform. A downward fold is a synform. The axis of a fold can be vertical, inclined, or even horizontal. If we know that the folded beds have not been overturned, then we can use the more specific terms: anticline and syncline. |
| 10.3 Faulting | Fractures (joints) typically form during extension, but can also form during compression. Faulting, which involves the displacement of rock, can take place during compression or extension, as well as during shearing at transform boundaries. Thrust faulting is a special form of reverse faulting. |
| Lab 10 Exercises | Block models are useful tools for examining and recognizing geologic structures in 3D. Writing a geologic history for the units shown on a block model is an excellent way to practice using the principles of stratigraphy to determine relative ages. |

# Mineral Identification Tables



**MINERALS WITH METALLIC LUSTRE**

H = hardness, SG = specific gravity

| | Streak | Cleavage / Fracture | H | SG | Other Properties | Mineral Name and Formula |
|---|---|---|---|---|---|---|
| **Hardness > 5.5** (harder than glass) | Distinct red-brown | No cleavage | 5 to 6.5 | 5.3 | Typically earthy lustre and red-brown colour. Rare steel grey variety has metallic lustre (specular hematite). | **Hematite** ($Fe_2O_3$) |
| | Grey-black | No cleavage, uneven fracture | 6 | 5.2 | Strongly magnetic. | **Magnetite** ($Fe_3O_4$) |
| | Greenish-black to brownish-black | No cleavage | 6 | 5 | Brassy yellow, tarnishes rusty brown. Cubic or pyritohedron crystal habit, often with striated faces. Also forms granular masses. | **Pyrite** ($FeS_2$) |
| **Hardness 2.5 to 5.5** (harder than fingernail, softer than glass) | Pale yellow | 6 good cleavage directions | 3.5 to 4 | 4 | Submetallic or resinous lustre. Yellow, red, green, brown, and black varieties possible. Streak smells like sulphur. | **Sphalerite** (ZnS) |
| | Greenish-black | No cleavage, uneven fracture | 3.5 to 4 | 4 | Golden yellow but often tarnished to bright purple-blue-yellow. May be confused with pyrite but does not form cubic crystals. | **Chalcopyrite** ($CuFeS_2$) |
| **Hardness < 2.5** (softer than fingernail) | Grey | 3 directions at 90° (cubic) | 2.5 | 7.5 | Bright lead grey coloured commonly cubic crystals. | **Galena** (PbS) |
| | Dark grey-black | Perfect in one direction, rarely seen | 1 | 1.75 | Silver-grey colour, very soft (writes on paper), feels greasy. | **Graphite** (C) |

## DARK MINERALS WITH NON-METALLIC LUSTRE

H = hardness, SG = specific gravity

| | Streak | Cleavage / Fracture | H | SG | Other Properties | Mineral Name and Formula |
|---|---|---|---|---|---|---|
| Hardness > 6.5 (harder than streak plate) | None (scratches streak plate) | No cleavage. Conchoidal fracture | 7 | 3.5 to 4.3 | Vitreous to resinous lustre. Variable colour (red to reddish brown most common). Commonly seen as equant 12-sided crystals that may appear rounded if small in size. | **Garnet family** (Complex Ca, Fe, Mg, Al, Cr, Mn isolated silicate) |
| Hardness 5.5 to 6.5 (harder than glass, softer than streak plate) | Colourless to pale green | No cleavage. Conchoidal fracture. | 6.5 to 7 | 3 to 3.3 | Olive green to yellow-green. Commonly form small, granular glassy crystals. | **Olivine** ($(Fe,Mg)_2SiO_4$) |
| | Colourless to pale green | 2 planes: 1 perfect, 1 poor, not at 90° | 6 to 7 | 3.3 | Pale green - yellow to dark green. Pistachio green common. | **Epidote** (Complex Ca, Al, Fe, OH ring silicate) |
| | Colourless to pale green | 2 directions at ~90° | 5 to 6 | 3.2 to 3.4 | Greenish-black to shades of green. Commonly seen as vitreous black short prismatic crystals. | **Pyroxene family (augite)** $(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$ |
| | Colourless to pale green | 2 directions not at 90° (56° and 124°) | 5 to 6 | 3 to 3.4 | Greenish-black to shades of green. Commonly seen as vitreous black elongate crystals. | **Amphibole family (hornblende)** $(Ca, Na)_{2–3}(Mg, Fe, Al)_5(Al, Si)_8O_{22}(OH, F)_2)$ |
| | White | 2 directions at ~90° | 6 | 2.6 | Variable colour (white to dark grey). Labradorite commonly dark blue-grey and irredescent. Striations on some faces. | **Feldspar family (anorthite)** ($CaAl_2Si_2O_8$) |
| | Distinct red-brown | No cleavage | 5 to 6.5 | 5.3 | Typically earthy lustre and red-brown colour. Rare steel grey variety has metallic lustre (specular hematite). | **Hematite** ($Fe_2O_2$) |
| Hardness 2.5 to 5.5 | Pale yellow | 6 good cleavage directions | 3.5 to 4 | 4 | Submetallic or resinous lustre. Yellow, red, green, brown, and black varieties possible. Streak smells like sulphur. | **Sphalerite** (ZnS) |
| Hardness < 2.5 (softer than fingernail) | Greenish-brown | Perfect in one direction | 2.5 to 3 | 3 | Dark-coloured (brown to black), flakes into thin elastic sheets | **Biotite** $(K(Mg,Fe)_3AlSi_3O_{10}(OH)_2)$ |
| | Yellow-brown | Rarely seen | 1 to 3 | 3.5 | Yellow-brown to dark brown, earthy lustre, powders easily. Often seen coating other minerals. | **Limonite** ($FeO(OH)_nH_2O$) |
| | White or colourless | Perfect in one direction, rarely seen | 2 to 2.5 | 2.6 to 3.3 | Shades of green, mica-like mineral. | **Chlorite** (Complex Fe-Mg phyllosilicate) |

## LIGHT MINERALS WITH NON-METALLIC LUSTRE

H = hardness, SG = specific gravity

| | Streak | Cleavage / Fracture | H | SG | Other Properties | Mineral Name and Formula |
|---|---|---|---|---|---|---|
| **Hardness > 6.5** (harder than streak plate) | None (scratches streak plate) | No cleavage. Conchoidal fracture | 7 | 2.65 | Vitreous lustre. Variable colour. Commonly seen as irregular-shaped glassy grains in rocks. Crystal habit is distinctive - elongate 6-sided prisms with pyramidal end. | **Quartz** ($SiO_2$) |
| | | 2 planes with different hardness | 7 and 4 | 3.6 | Vitreous or pearly lustre. Pale blue to white. Crystals commonly appear bladed (elongate but flat). | **Kyanite** ($Al_2SiO_5$) |
| **Hardness 5.5 to 6.5** (harder than glass, softer than streak plate) | White | 2 directions at ~90° | 6 | 2.6 | Variable colour (white to dark grey). Striations on some faces. | **Feldspar family (albite)** ($NaAlSi_3O_8$) |
| | | | | | Variable colour (white to pink). No striations. May have exsolution lamellae (irregular wavy lines of a different colour, typically sub-millimetre in width). | **Feldspar family (potassium feldspar)** ($KAlSi_3O_8$) |
| **Hardness 2.5 to 5.5** (harder than fingernail, softer than glass) | Pale yellow | 6 good cleavage directions | 3.5 to 4 | 4 | Submetallic or resinous lustre. Yellow, red, green, brown, and black varieties possible. Streak smells like sulphur. | **Sphalerite** ($ZnS$) |
| | White or colourless | 4 directions | 4 | 3.2 | Vitreous lustre. Colour variable (green, purple, yellow, colourless). | **Fluorite** ($CaF_2$) |
| | | 3 directions at 90° (cubic) | 3 to 3.5 | 4.5 | Vitreous lustre. Colourless to white or cream. Distinctly high S.G. for a non-metallic mineral. | **Barite** ($BaSO_4$) |
| | | 3 directions not at 90° (all at ~75°; rhombic) | 3 | 2.7 | Vitreous lustre. Commonly white to colourless. Forms rhombohedral shapes. Reacts vigorously with dilute HCl. | **Calcite** ($CaCO_3$) |
| | | 3 directions at 90° (cubic) | 2.5 | 2 | Vitreous lustre. Colourless to white cubic crystals, often seen with sylvite (KCl), which can be variably coloured. Salty taste. | **Halite** ($NaCl$) |
| **Hardness < 2.5** (softer than fingernail) | White or colourless | Perfect in one direction | 2 to 2.5 | 2.8 | Silky to pearly lustre. Colourless to pale gold. Breaks into transparent elastic sheets along cleavage plane. | **Muscovite** ($K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$) |
| | | Perfect in one direction, rarely seen | 2 to 2.5 | 2.6 | Earthy lustre. Dull white and powdery. Distinctly earthy odour. | **Kaolinite** ($Al_2Si_2O_5(OH)_4$) |
| | | 3 cleavage directions: 1 perfect, 2 good. Only 1 typically seen. | 2 | 2.3 | White to transparent. May be fibrous with silky lustre (selenite) or massive. | **Gypsum** ($CaSO_4{\cdot}2H_2O$) |
| | | Perfect in one direction, rarely seen | 1 | 2.7 to 2.8 | Greasy or soapy feel. Pearly lustre. Colour variable (pale green, yellow, grey and silver-white) | **Talc** ($Mg_3Si_4O_{10}(OH)_2$) |

# Rock Classification Tables

## Igneous Rocks

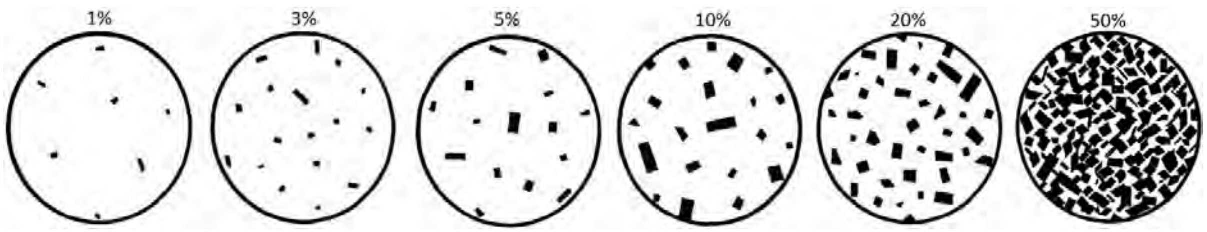



*Figure A: Visual guide to estimating the proportions of dark minerals in light-coloured rocks.*

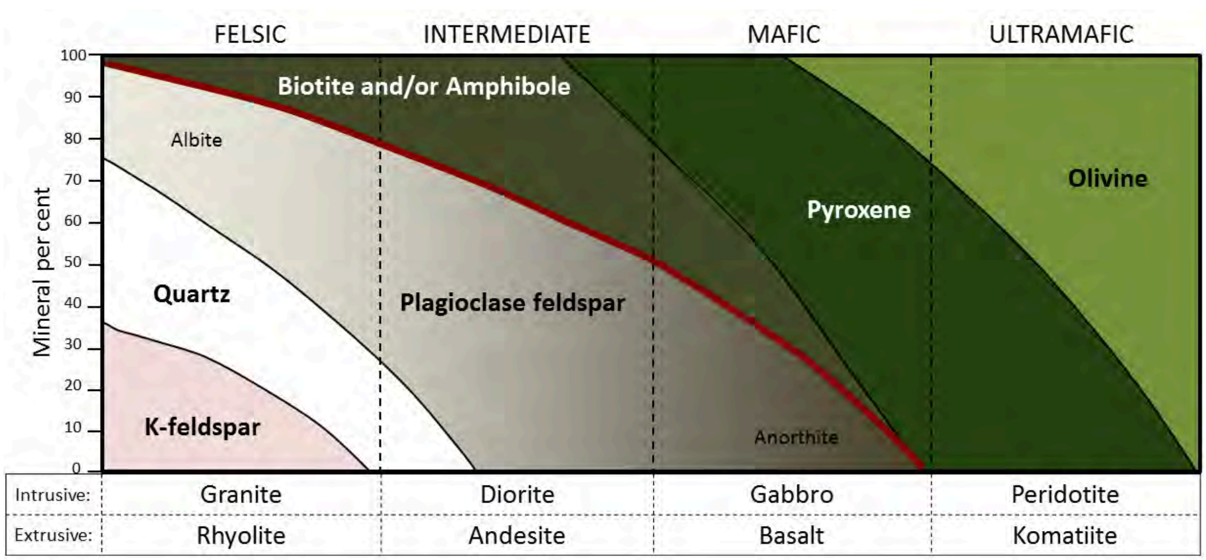



*Figure B: A simplified classification diagram for igneous rocks based on their mineral compositions. Note that glassy igneous rocks **pumice** and **obsidian** are not included on this diagram.*

## Sedimentary Rocks

**Table A: The Udden-Wentworth grain-size scale for classifying sediments and the grains that make up clastic sedimentary rocks**

| Type | Description | Size range (millimetres, mm) | Size range (microns, µm) |
|---|---|---|---|
| **Boulder** | large | 1024 and up | |
| | medium | 512 to 1024 | |
| | small | 256 to 512 | |
| **Cobble** | large | 128 to 256 | |
| | small | 64 to 128 | |
| **Pebble (Granule)** | very coarse | 32 to 64 | |
| | coarse | 16 to 32 | |
| | medium | 8 to 16 | |
| | fine | 4 to 8 | |
| | very fine | 2 to 4 | |
| **Sand** | very coarse | 1 to 2 | 1000 to 2000 |
| | coarse | 0.5 to 1 | 500 to 1000 |
| | medium | 0.25 to 0.5 ($^1/_4$ to $^1/_2$ mm) | 250 to 500 |
| | fine | 0.125 to 0.25 ($^1/_8$ to $^1/_4$ mm) | 125 to 250 |
| | very fine | 0.063 to 0.125 ($^1/_{16}$ to $^1/_8$ mm) | 63 to 125 |
| **Silt** | very coarse | | 32 to 63 |
| | course | | 16 to 32 |
| | medium | | 8 to 16 |
| | fine | | 4 to 8 |
| | very fine | | 2 to 4 |
| **Clay** | clay | | 0 to 2 |

**Table B: The main types of clastic sedimentary rocks and their characteristics. You are expected to be able to identify the bolded rock names in this course.**

| Group | Examples | Characteristics |
|---|---|---|
| **Conglomerate** | | Dominated by rounded clasts, granule size and larger (>2 mm), poorly to very poorly sorted |
| Breccia | | Dominated by angular clasts, granule size and larger (>2 mm), poorly to very poorly sorted |
| Sandstone | **quartz sandstone** | Dominated by sand (1/16 to 2 mm), greater than 90% quartz, range of roundness and sorting possible |
| | **arkose** (feldspathic sandstone) | Dominated by sand (1/16 to 2 mm), greater than 10% feldspar, range of roundness and sorting possible |
| | lithic wacke | Dominated by sand (1/16 to 2 mm), greater than 10% rock fragments, greater than 15% silt and clay, range of roundness and sorting possible |
| Mudrock | mudstone | Greater than 75% silt (1/256 to 1/16 mm) and clay (<1/256 mm), not bedded, well-sorted, grains too fine to judge roundness using hand lens |
| | **shale** | Greater than 75% silt (1/256 to 1/16 mm) and clay (<1/256 mm), thinly bedded, well-sorted, grains too fine to judge roundness using hand lens |

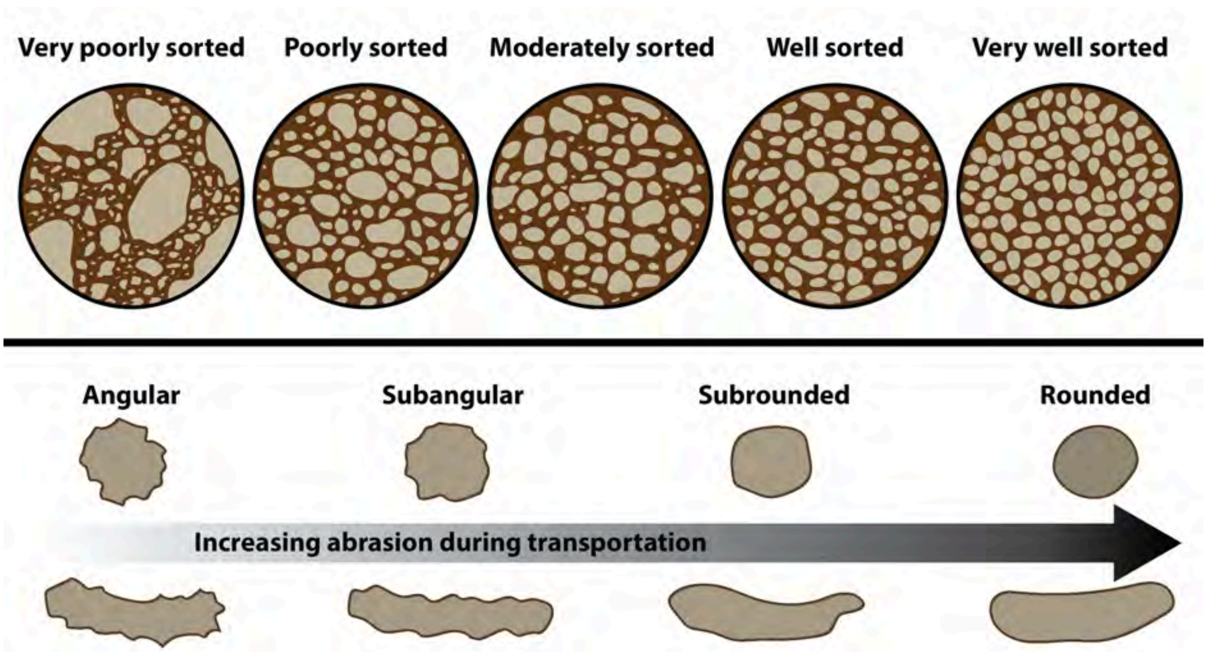



*Figure C: A visual reference for descriptions of sorting (top) and roundness (bottom) of sediments and grains in clastic sedimentary rocks.*

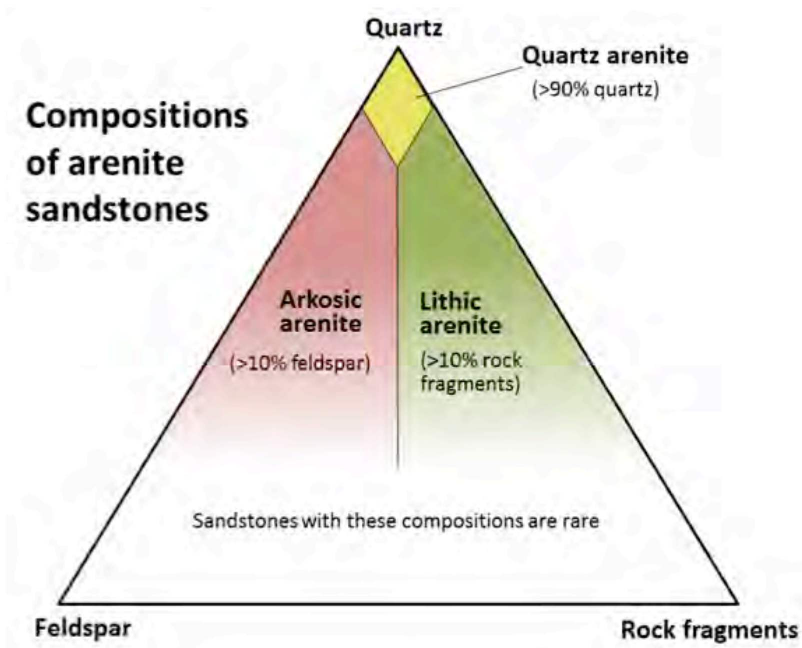



*Figure D: A compositional triangle for arenite sandstones, with the three most common components of sand-sized grains: quartz, feldspar, and rock fragments. Arenites have less than 15% silt or clay. Sandstones with more than 15% silt and clay are called **wackes** (e.g., quartz wacke, lithic wacke).*

**Table C: Classification chart for chemical sedimentary rocks**

| Composition | Texture | Distinctive Properties | Rock Name |
|---|---|---|---|
| **Calcite ($CaCO_3$)**<br>**Note that all lime-stones will react with dilute HCl.* | Crystalline | Crystalline; fine to coarse grained | **Crystalline limestone** |
| | Fossiliferous | Various fossil fragments well cemented together | **Fossiliferous limestone** |
| | Oolitic | Comprised of ooids (spheroidal particles typically <2 mm in diameter) | **Oolitic limestone** |
| | Bioclastic | Visible shell fragments weakly cemented together | **Coquina** |
| | Bioclastic | Soft rock made of microscopic shells | **Chalk** |
| **Quartz ($SiO_2$)** | Microcrystalline | Microcrystalline; hardness of ~7 (can scratch glass); may exhibit conchoidal fracture | **Chert** (note that dark coloured varieties may be called **flint** and red coloured varieties may be called **jasper**) |
| **Halite (NaCl)** | Crystalline | Crystalline; fine to coarse grained; commonly forms cubic crystals; tastes salty | **Rock salt** |
| **Gypsum ($CaSO_4 \cdot H_2O$)** | Crystalline | Crystalline; fine to coarse grained; hardness ~2 (can scratch with fingernail) | **Rock gypsum** |
| **Organic material (plant fragments)** | Amorphous | Black brittle rock with amorphous texture; low density | **Coal** |

## Metamorphic Rocks

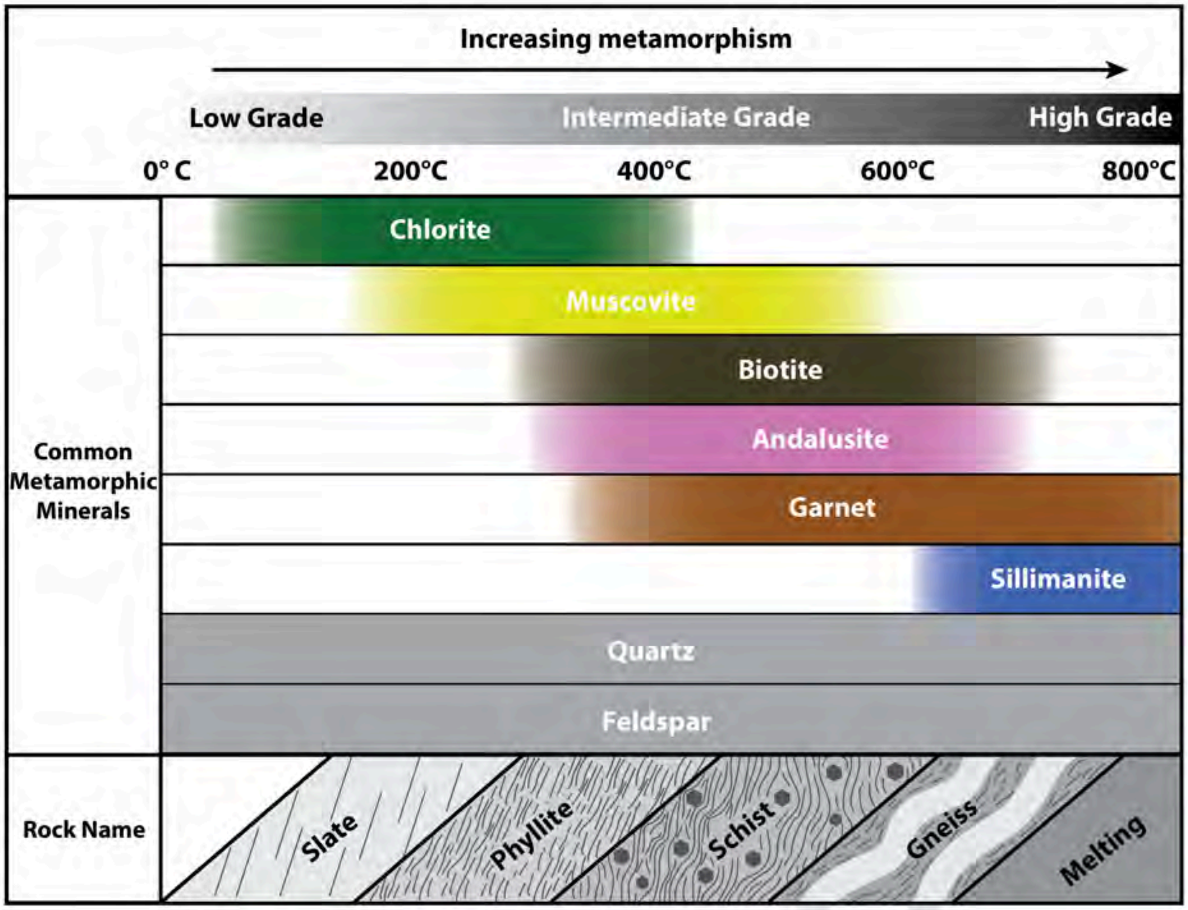



*Figure E: Metamorphic grades, common metamorphic index minerals, and corresponding rock names for a mudrock protolith under increasing metamorphism (increasing temperature and pressure).*

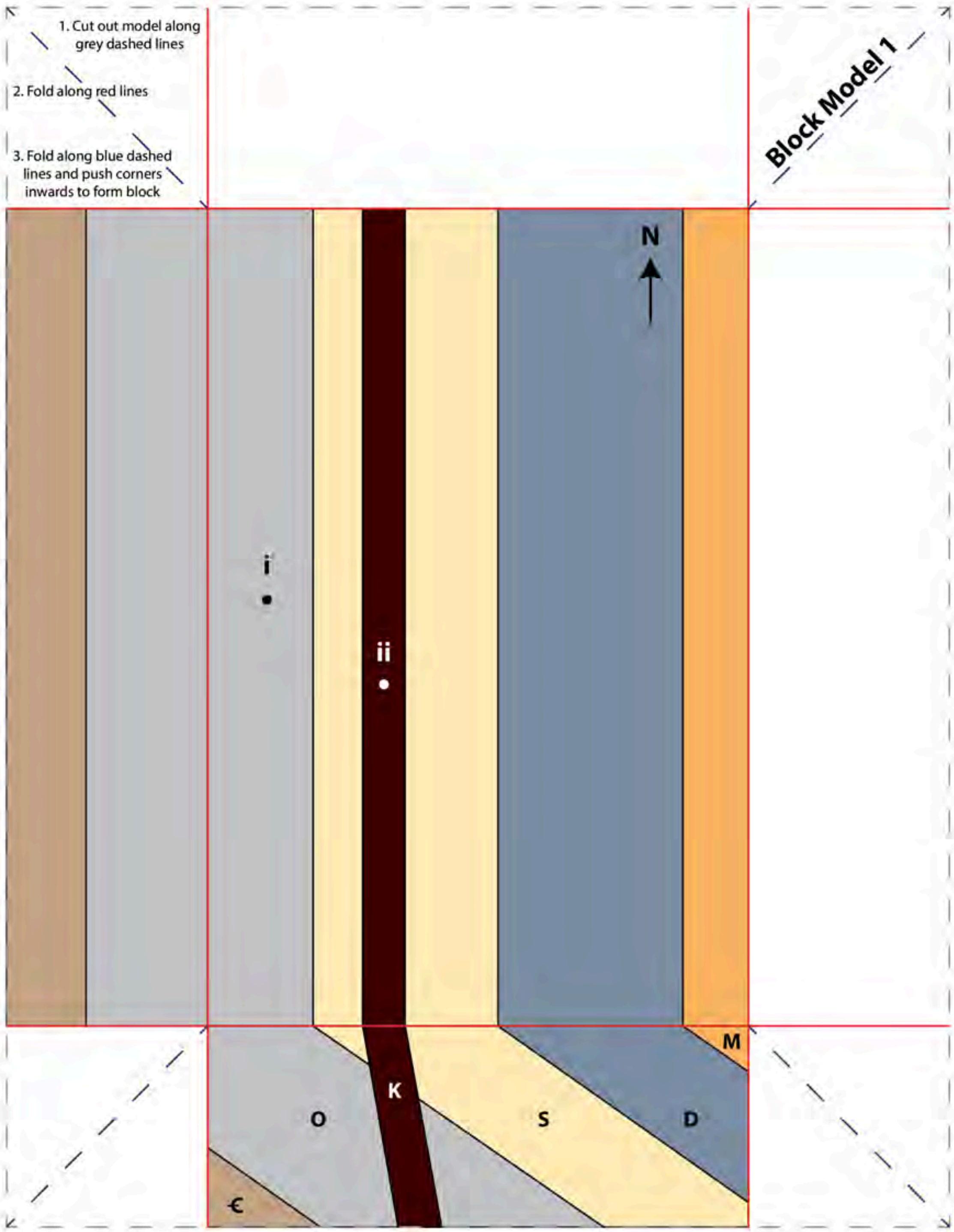
**Table D: A rough guide to the types of metamorphic rocks that form from different protoliths at different grades of regional metamorphism. You are expected to know the rock names indicated in bold font.**

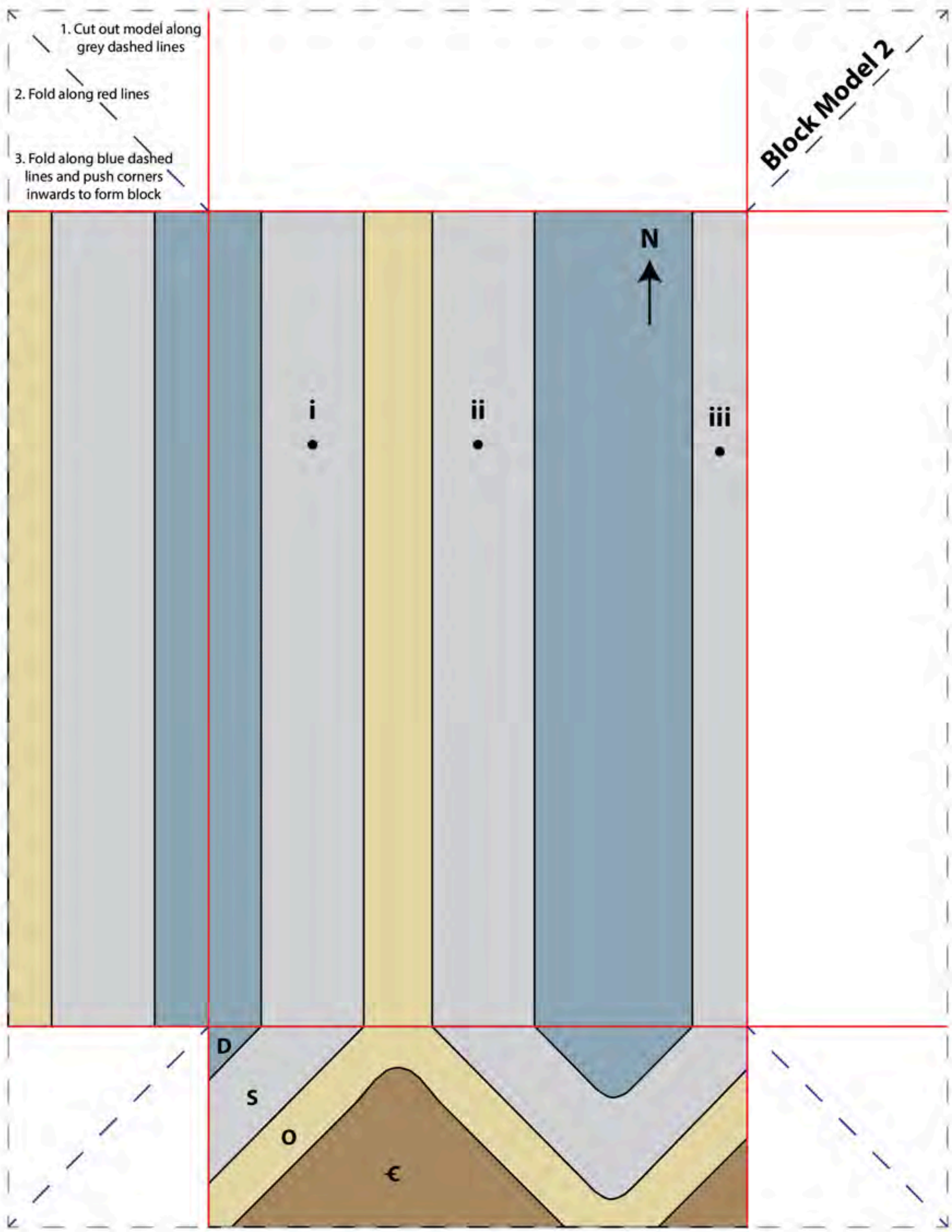
| Protolith | Very Low Grade (150-300°C) | Low Grade (300-450°C) | Medium Grade (450-550°C) | High Grade (Above 550°C) |
|---|---|---|---|---|
| Mudrock | **slate** | phyllite | **schist** | **gneiss** |
| Granite | no change | no change | almost no change | granite gneiss |
| Basalt | **greenschist** | **greenschist** | amphibolite | amphibolite |
| Sandstone | no change | little change | **quartzite** | **quartzite** |
| Limestone | little change | **marble** | **marble** | **marble** |

## Media Attributions

- Figures A, B, D: © Steven Earle. CC BY.

# Appendix 5: Block Models




1. Cut out model along grey dashed lines
2. Fold along red lines
3. Fold along blue dashed lines and push corners inwards to form block
Block Model 2
N
i
ii
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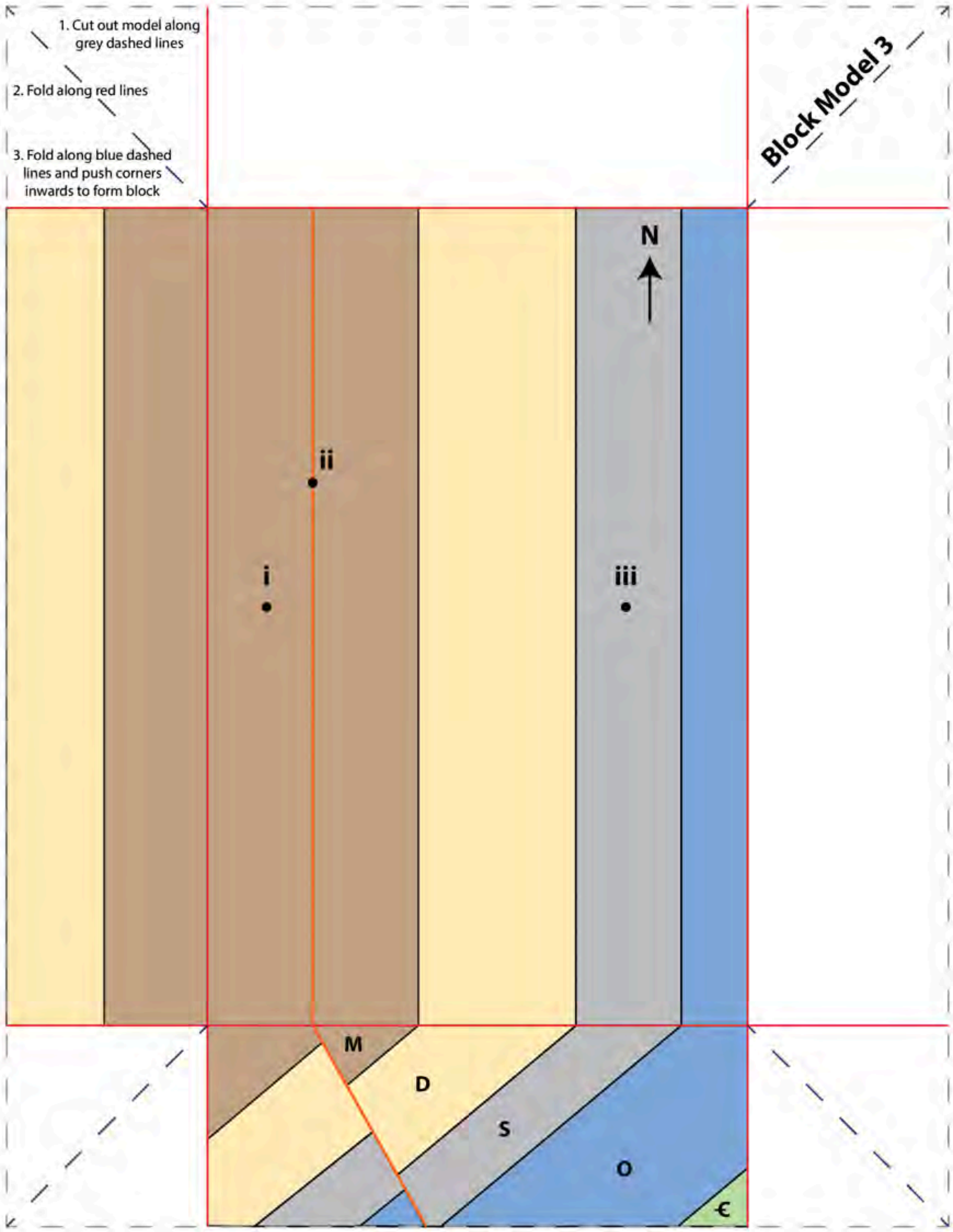
1. Cut out model along grey dashed lines
2. Fold along red lines
3. Fold along blue dashed lines and push corners inwards to form block
Block Model 3
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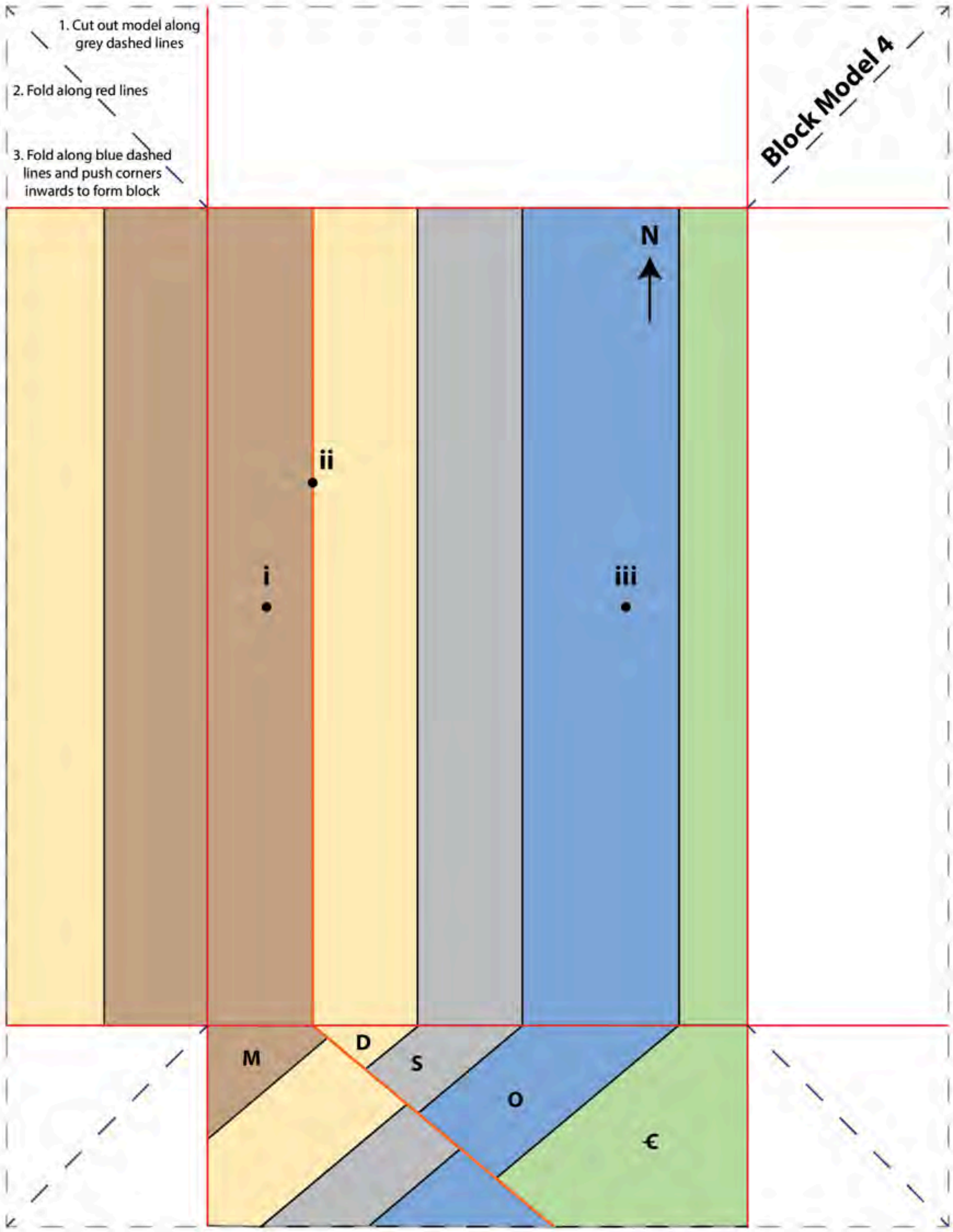
1. Cut out model along grey dashed lines
2. Fold along red lines
3. Fold along blue dashed lines and push corners inwards to form block
Block Model 4
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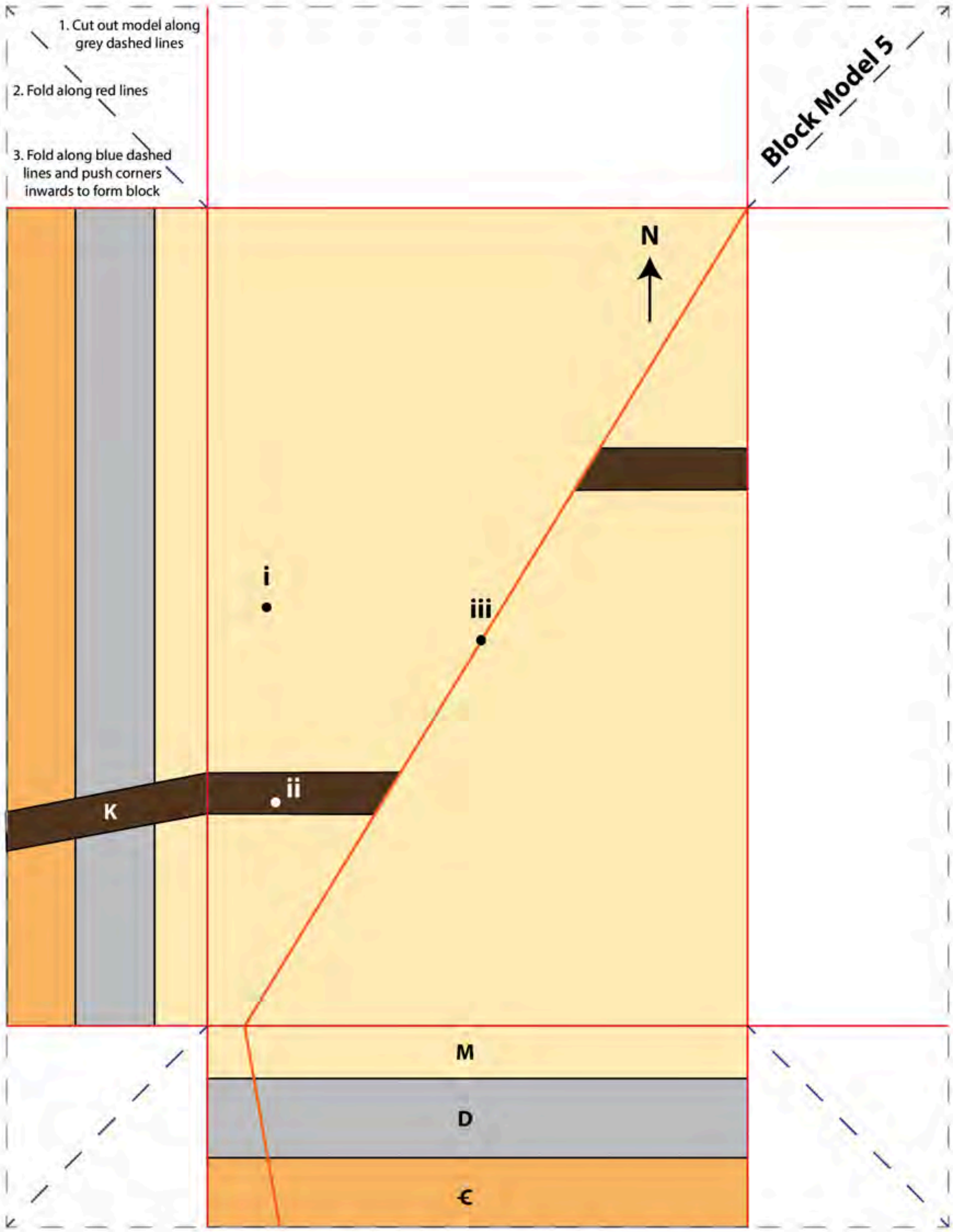
1. Cut out model along grey dashed lines
2. Fold along red lines
3. Fold along blue dashed lines and push corners inwards to form block
Block Model 5
N
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ii
iii
K
M
D
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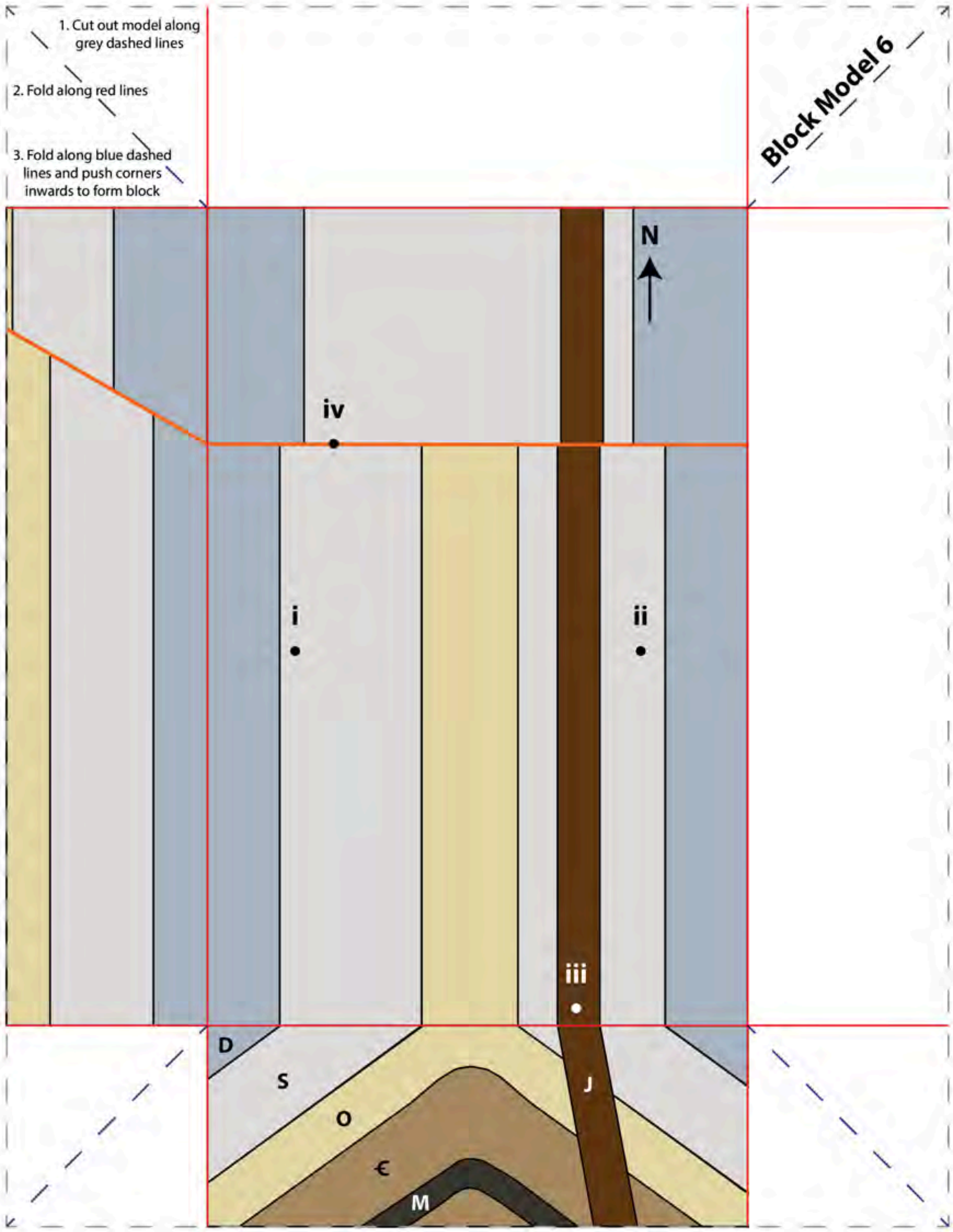
1. Cut out model along grey dashed lines
2. Fold along red lines
3. Fold along blue dashed lines and push corners inwards to form block
Block Model 6
N
iv
i
ii
iii
D
S
O
J
€
M