Department of Earth Sciences
City College of San Francisco
Professor Katryn Wiese

Geology 10 LAB

Spring 2021 Manual

Geology 10 Lab Manual

Author: Katryn Wiese

Manual Produced By Katryn Wiese
(send edits/comments to katryn.wiese@mail.ccsf.edu)

Cover image from Saddlebag Lake Area, High Sierra, Hoover Wilderness

Table of Contents

Measurements – Numbers and Angles

NEEDED SUPPLIES:

- Ruler that shows inches AND centimeters
- Protractor to measure angles (often these also come with a ruler on the bottom, so you get 2 in one) – you will need one for the first ½ of the class, so try to buy your own. 😊
- Pencil and eraser
- Calculator

These exercises cover measurement skills that you will be using in future labs. Since these skills often cause big time issues in future labs, because of varied math skill levels, we use the first lab of the semester to get everyone up to speed. If you are already strong in these areas, you should finish today's lab quickly. If, however, you are weaker, you may need more time and might need to work on it outside class time over the next week. If you're struggling, reach out for help. Come to office hours or make an appointment with the instructor. But just be sure you take the time now to master this material before proceeding further in this class. If you do not think your math skills are up to this task, consider re-enrolling in this course another semester after you've built up your math skills. *Discuss with instructor if any concerns!*

Metric system

The metric system is the only system used by scientists globally and hence will be the system we use throughout this course.

- 1 km = 1 kilometer = 1000 meters (m) *(1 km = 0.614 miles)*
- 1 m = 1 meter = 100 centimeters (cm) = 1000 millimeters (mm) *(1 m = 1.09 yards)*
- 1 cm = 1 centimeter = 10 millimeters (mm) *(1 cm = 0.394 inches)*

Inequalities

< is a **Less than** sign. Example: 6 < 7 means 6 is less than 7. X < 7 means any number less than 7.
> is a **Greater than** sign. Example: 7 > 6 means 7 is greater than 6. X > 7 means any number greater than 7.
In science we use inequalities regularly to describe error of measured numbers and to provide estimates that sit within a range of numbers. As such, you will need to be able to read an inequality correctly.
(The mouth of the alligator opens towards the larger meal!)

- ***6 meters > 2 meters*** means 6 meters is greater than 2 meters.
- ***4 meters < 10 meters*** means that 4 meters is less than 10 meters.
- ***2 meters < X ≤ 4 meters*** means X is a number greater than 2 meters and less than or equal to 4 meters.

Precision

How many times have you completed a calculation on your calculator and wondered how to round your answer? For example, take 10 and divide it by 3. Your calculator will read 3.3333333. What does that mean? Are all those 3s after the decimal necessary? Meaningful? To help us understand the answer to this question, we first have to be sure we correctly and consistently describe the precision of a number – the depth of information provided in terms of scale or depth. The number **1.2 cm is precise to 1 decimal place**

- The number **1.22 is precise to 2 decimal places**. It is MORE precise than 1.2 cm.
- The number **1 cm is precise to the ones place**. It is LESS precise than 1.2 cm or 1.22 cm.
- The number **320 cm is precise to the tens place** because the 0 with no decimal means it could have been rounded, meaning not 310 cm and not 330 cm. It is the LEAST precise of all the numbers in this list. *What do we do then when the measurement really is 320 cm NOT 321 or 319? We have to add a range to it: 320 cm +/- 0.5 cm. Otherwise, there's no way for our audience to distinguish the differences, and we must assume the least precision.*
- The number **320.000 cm is precise to three decimal places**. It is the MOST precise of all the numbers in this list.

Precision and Measurements

When we take measurements, our instruments have a limit to their precision and thus our answers are rounded to the smallest graduation of measurement. *(HINT: Want to know what's been measured? There should be a unit attached! Examples: 10 kg or 6 meters.)* We call the smallest graduation of measurement for an instrument its **PRECISION**.

- A thermometer that we use at home to take our body temperature can indicate 98.6°F or 98.7°F, but no more precise than 1 decimal place.

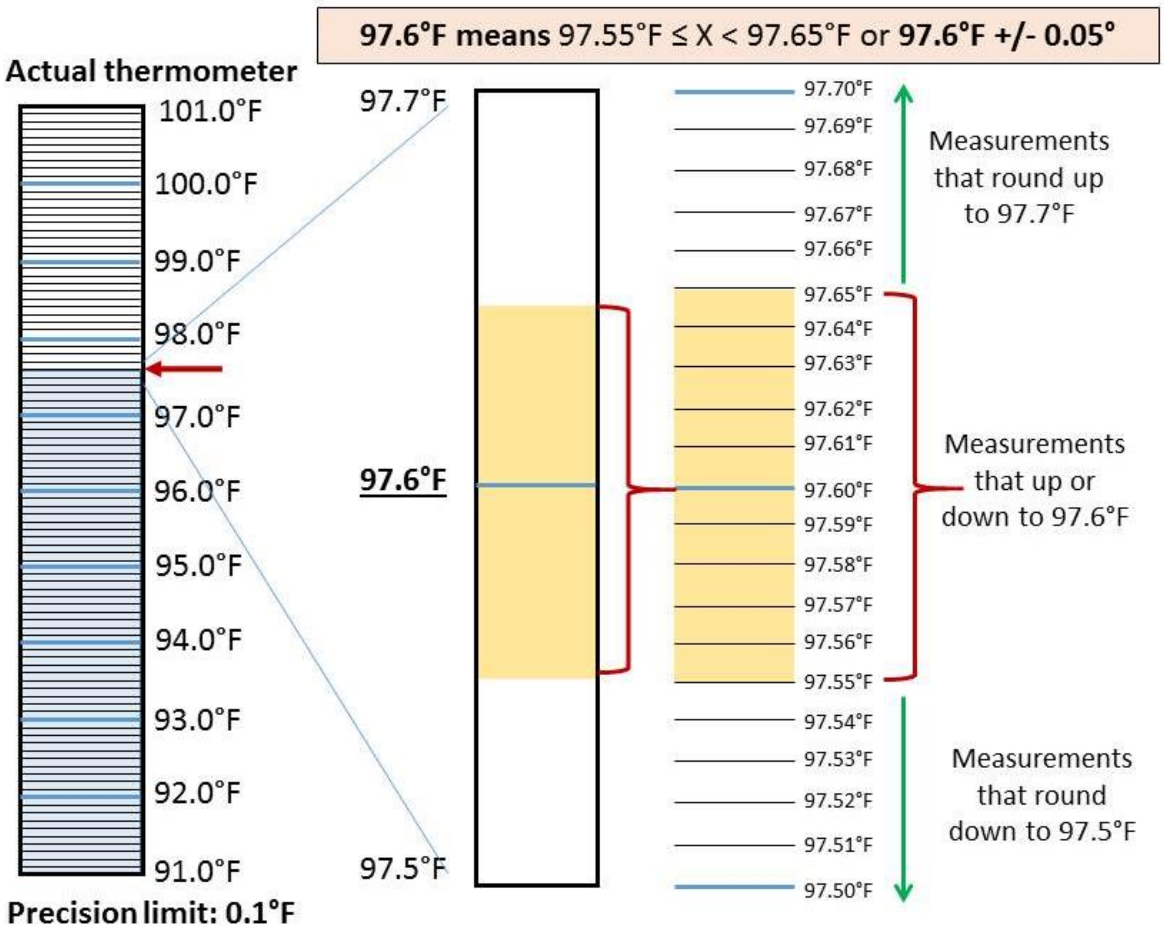
- A meter stick that we use in the classroom has millimeters as the smallest graduation. So we can use it measure to the nearest millimeter (0.001 m), but no more.

Since all measuring devices have a limit to their precision, there will always be a **range** (or error) to our measurements, dependent on that precision.

Example: 98.6°F means NOT 98.7°F and NOT 98.5°F. If our measurement lands between graduations on the thermometer, we'll round up or down as is most appropriate. Values between 98.6°F and 98.7°F are rounded up to 98.7°F if ≥ 98.65°F or down if < 98.65°F.

- 98.64°F rounds down to 98.6°F. As does 98.63°F, 98.62°F, 98.61°F, and 98.60°F.
- 98.55°F rounds up to 98.6°F, as does 98.56°F, 98.57°F, 98.58°F, and 98.59°F.

SO, 98.6°F really means everything from 98.55°F to 98.64°F. Although it is not exactly equivalent, it is also similar to saying 98.6°F +/-0.05°F. *(See following image for visual of this concept.)*



More error will be added to a measurements when an instrument is difficult to read or hold. If you can't align it precisely, for example, then you can't be sure you are reading the correct measurements. In that case, the user adds additional error to the measurements to reflect that situation.

Example: 98.6°F +/- 0.3°F means I wasn't sure I could read it as precisely as the instrument allowed or it fluctuated during measurement between a range of numbers, so it could have been as high as 98.9°F or as low as 98.3°F.

ALL MEASURED NUMBERS (UNITS ATTACHED) SHOULD COME WITH AN ERROR. IF NONE IS GIVEN, THEN YOU ASSUME THE ERROR TO BE +/- ½ THE MEASUREMENT OF THE NEXT NUMBER PLACE).

- *12.3 cm with no error attached is really 12.3 +/- 0.05 cm*
- *12.3 cm +/- 0.1 cm has additional error than the measurement tool maximum precision, which means the user of the instrument felt their own limitations in using the instrument were higher*

Measurements – Prereading Exercises

1. Circle which of the numbers here is the MOST precise.
   100 m | 110 m | 111 m | 111.1 m

2. Circle which of the numbers here is the LEAST precise.
   1000 m | 79 m | 1 m | 0.1 m

3. Find a meter stick or metric ruler that shows inches and centimeters. Insert correct symbol:
   1 cm _______ 1 inch

4. Use symbols and variable X to describe
   a measurement between 6 meters and 18 meters.

5. Use symbols and variable X to describe
   a measurement that is less than or equal to 2.5 meters.

6. Translate the following math symbols into English: 10 < X <90 cm

7. Look again carefully at your ruler and indicate its maximum precision (on metric side).
   (What is the smallest gradation of measurement visible on the tool?)

8. Use this meter stick or metric ruler to measure the width of this page in cm. Give the measurement below and its range or error. *(Incorporate the error that you experience as the user/holder of your instrument.)*

9. Pick another object in the room. Describe the object, and give the measurement below and its range or error. *(Incorporate the error that you experience as the user/holder of your instrument.)*

10. If you error is greater than the precision of the instrument, explain why. What prevented you from getting as precise as the instrument could get?

11.

12. The measured number, 2.9 cm, has what precision and represents what range or error?

13. The measured number, 3200 cm, has what precision and represents what range or error?

14. If one person measures a sample of chemical powder to weigh 1 g *+/- 0.5 g (range is 0.5 g to 1.5 g),* and another person measures a second sample that weighs 1.3 g *+/- 0.05 g – more precise (range is 1.25 g to 1.35 g*), and we add these two samples together for an experiment, what is the result?
    CIRCLE: 2.3 g *(range 2.25 g to 2.35* g) or 2 g *(range 1. 5 g to 2.5 g)* **Why did you pick the answer you did?**

Measurements – Lab Exercises

Rounding

Let's return now to the calculator problem. If I measure an object to be 2.8 cm long, and then I divide that into 3 equal pieces, how long is each piece? Using a calculator, 2.8 cm divided by 3 is 0.93333333 cm. Does it make sense to keep all those decimals when I know the original measurement only to one decimal place? We can't make a measurement more precise just by breaking it into 3 pieces, so we have to round it to match the precision of our original number. To round, determine first the place you'll round to. That's the limit of precision you're allowed. Call that number MAX. Now look at the number to the right of MAX. If it is ≥ 5, round MAX up, meaning add 1 to it. If the number to the right is < 5, no change!

- $32.5 rounded to the **ones place** is $33 | $32.4 rounded to the **ones place** is $32.
- $56,712 rounded to the **tens place** is $56,710 | $56,712 rounded to the **hundreds place** is $56,700
- $56,712 rounded to the **thousands place** is $57,000 | $56,712 rounded to the **ten thousands place** is $60,000

15. Round $45,325 to the thousands	16. Round $3.6258 to two decimal places	17. Round $5.56 to the ones place

Rounding and maintaining precision during mathematical calculations

Basic rule: if your calculation involves any measured numbers (recognizable because they come with a unit!), and those numbers all have the same unit, and your result also has the same unit, then round your answer so it is as precise as the **least precise** of any of your starting **measurements**.

- 12.6 cm + 3 cm = 15.6 cm rounded to answer: 16 cm (precise to same as 3 cm, the least precise).
- 12.6 cm x 1.3 = 16.38 cm rounded to answer: 16.4 cm (precise to same as 12.6 cm, the only measurement).

Calculate the following and round answer to the correct precision. (Show original answer and rounded one.)

18. 12.7 cm + 6.43689 cm =	19. 12.7 cm – 3 cm =
20. Take your page width measurement from Q7 and divide it by 3, to figure out the width of 1/3 of this page. *Remember to keep your error in your final answer!*	21. Take your object measurement from Q8 and divide it by 3, to figure out the height of 1/3 of the table. *Remember to keep your error in your final answer!*

Unit conversion

Whenever you want to convert units from one into another, follow this simple technique that ALWAYS works:

1. Turn your original number into a fraction over 1.
2. Multiply this fraction by another fraction, one that equals 1: the conversion factor. Put the number with the units you want to cancel out on the bottom and the number with the units you want to end with on the top. (So the original unit cancels, and the new unit remains).

For example, to convert 3605 cm to inches:

$$\frac{3605\text{ cm}}{1} \times \frac{\_\_\_}{\_\_\_} = ?\text{ in} \rightarrow \frac{3605\text{ }\cancel{\text{cm}}}{1} \times \frac{\text{in}}{\cancel{\text{cm}}} = ?\text{ in} \rightarrow \frac{3605\text{ }\cancel{\text{cm}}}{1} \times \frac{1\text{ in}}{2.54\text{ }\cancel{\text{cm}}} = \frac{3605\text{ in}}{2.54} = 1419\text{ in}$$

How do we round our answer? When converting units, if the starting unit and ending units are comparable, like inches and centimeters or miles and kilometers, then we can just keep the initial precision. Make them match. ***NOTE:*** *we should use conversion factors that are more precise than our actual measured numbers so we can ignore their precision when rounding.*

22. Convert 34.2 km to miles. Conversion factor: 1 km = 0.6214 mi. (*km and miles are similar, so keep original precision)* **Show ALL work, with units.**

23. Convert 12 cm to inches. Conversion factor: 1 in = 2.54 cm. (*cm and in are similar, so keep original precision)*
 Show ALL work, with units.

What do we do when our mathematical calculation changes the units considerably, so we no longer know what precision to maintain? Answer: we have to carry our range/error along and then use it to round our final answer. How? We run the computation 3 times:

1. The first time with the original numbers
2. The second time with range/error end members that would produce the largest answer.
3. The third time with range/error end members that would produce the smallest answer.

We then compare the range end member calculations and see at what precision they start to vary. That's the maximum precision we keep for our original calculation, so we return to that original calculation and round accordingly.

Example: Convert 2111 m to km

$\frac{2111\text{m}}{1} \times \frac{\_\_\_\_}{} = ?\text{ km} \rightarrow \frac{2111\cancel{\text{m}}}{1} \times \frac{\text{km}}{\cancel{\text{m}}} = ?\text{ km} \rightarrow \frac{2111\cancel{\text{m}}}{1} \times \frac{1\text{ km}}{1000\cancel{\text{m}}} = \frac{2111\text{ km}}{1000} = 2.111\text{ km}$

How to round? 2111 m could be as big as 2111.4 m or as low as 2110.5 m. Now we solve the problem for the range/error limits, – 2111.4 m and 2110.5 m. Comparing where these values start to vary from each other tells us our precision.

RANGE: $\frac{2111.4\cancel{\text{m}}}{1} \times \frac{1\text{km}}{1000\cancel{\text{m}}} = 2.1114\text{ km}$ $\quad \frac{2110.5\cancel{\text{m}}}{1} \times \frac{1\text{km}}{1000\cancel{\text{m}}} = 2.1105\text{ km}$

Range is 2.1105 to 2.1114 km (the first place to change is the third decimal place; so we round original to this place).

ANSWER: 2.111 km

24. Convert 6310 ft to miles. Conversion factor: 5,280 ft = 1 mi. (It could be as big as 6314 feet or as low as 6305 feet.) (*Unit change is considerable, so use the 3-calculation rounding/precision technique described above.)* **Show ALL work, with units.**

Measuring angles

We use a protractor to measure angles made between two nonparallel lines. To ensure you're using the protractor correctly, first ask yourself, where is 0° is in your diagram. Once you find that, line the protractor up so the 0 line along the bottom of the protractor points at or lines up along the 0° line on your diagram. The T in the center of your protractor zero line should be placed at the intersection of your angle lines. Then read from 0° up. Notice that all protractors have two sets of measurements on the outside, 0° to 180° in one direction and the opposite for the other direction. Be sure you're reading the angles that start at 0° at your 0° line.

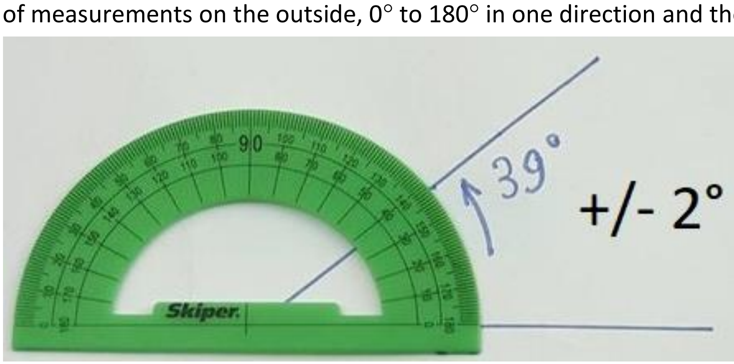
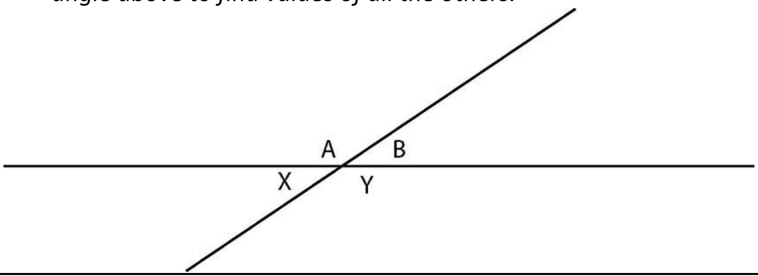


Image: wikiHow website on how to use a protractor. Link on lab website.

Notice how the center of the protractor goes through the middle of where your two lines intersect, so it can measure the angle between them. Error of 2° is limit of tool and eye/hand used to measure!

25. For the image on the below, use a protractor to measure all angles. Remember, since you're using an instrument to make a measurement there SHOULD be some error. Include that! *HINT: Notice that you need to measure only one angle above to find values of all the others.*



A: ______________

B: ______________

X: ______________

Y:______________

Adding and subtracting angles

1 degree (1°) can be broken into 60 equal pieces, each called 1 minute (1'); each minute is further divided into 60 equal pieces, each called 1 second (1"). When adding or subtracting angles, line up like units and add or subtract those as needed, then borrow or carry as needed so you don't end up with more than 60 seconds or 60 minutes in your answers. *Examples:*

36' + 45' = 81' or 1° + 21'	23° 11' 45" → 22°70'105" - 7° 44' 59" - 7°44'59" = 15°26'46"	45" – 59" would give a negative number, as would 11'-44', so we borrow before we subtract. Subtract 1° from 23° to get 22° + 60'; add 60' to 11' to get 71'; borrow 1' from 71' to get 70' + 60; add the 60" to 45" to become 105".

26. 32° 45' 36" + 3° 25' 52" = • • • • •	27. 32° 45' 36" – 3° 25' 52" =

When converting degrees, minutes, or seconds, treat similarly to the unit conversion problems above. **Examples:**

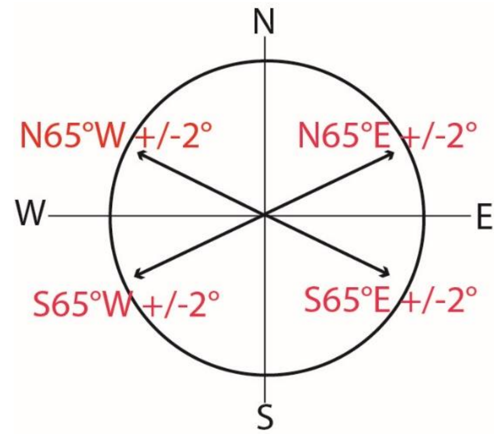
42.5° = 42° 30' $\left(\frac{0.5°}{1} \times \frac{60'}{1°} = 30'\right)$	42.125° = 42° 7' 30" $\left(\frac{0.125°}{1} \times \frac{60'}{1°} = 7.5'\right)$ $\left(\frac{0.5'}{1} \times \frac{60"}{1'} = 30"\right)$

28. 3 ¼ ° = _________° _________' _________"	29. 45.825° = _________° _______' _______"

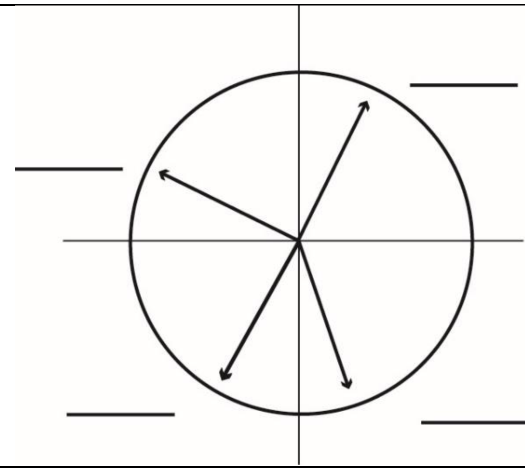
Orientation & Bearing

Orientation or bearing are angle measurements that describe the direction relative to north that someone is moving or looking. Geologists measure bearing of an arrow or sightline as a number of degrees east or west of North or east or west of South, depending on whether the arrow points towards the northern hemisphere or southern hemisphere. For example: N15°W means face north, then rotate 15° towards the west. S45°E means start facing south and then rotate 45° towards the east. Note: your angle of rotation must always be ≤ 90°. That's the format a geologist uses to describe the orientation of a line or arrow or direction you're facing (bearing) or direction you're traveling (heading) on a map. The last two pages of your Measurements lab describe this process AND include the way that oceanographers describe and format that orientation as well. Both are provided because you'll see different formats depending on what tool you're using. An oceanographer measures the angle always as a number from 0 to 360°, measured clockwise from north. Example: 75° means "face north and rotate 75° to your right."

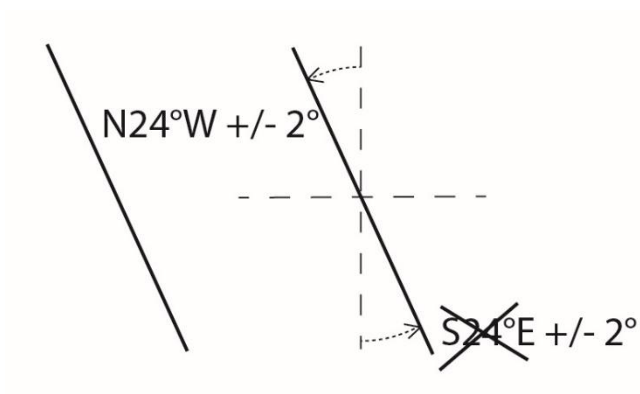
IN THIS CLASS, please always use geologist format, so that means you'll have to convert other formats.



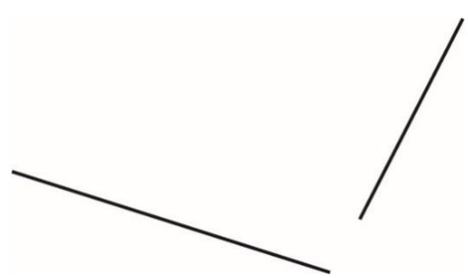
30. How would a geologist give the bearings of the lines in this image? (See examples above to help.) Give error/range.



If lines do not have a direction (aren't facing or pointing a specific way), then the standard for geologic orientations is to measure always the value from North (NX°W or NX°E where X is the actual angle and is ≤ 90°). In other words, if no arrow, then make your own, so the line points into the northern half of the circle. EXAMPLE: (First draw your own N-S-E-W cross-hairs across the line.) Give error/range.

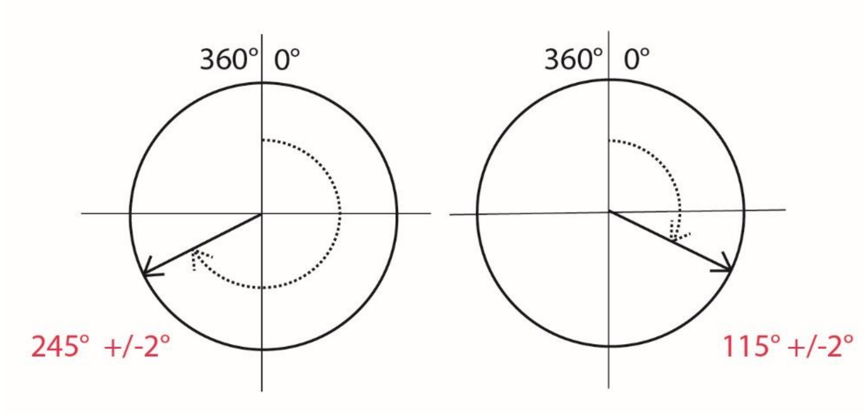


31. What is the orientation of these lines, according to **geologists**? (You can draw your own circle if helpful.) *(See example.)* Give error/range.



Bearings for Oceanographers
Final note: Compasses, which we'll use next week, often show angles using two methods – the one we learned above – the Geologist's method – and the one that's described here for Oceanographers. Oceanographers measure bearings as an angle between 0 and 360° always measured clockwise from North.

Be sure you know which compass reading you're using when you pick up a compass.



Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Evaluate instrument precision for rulers and protractors	A | B | C | D | F	
Evaluate error on given measurements and propagate those correctly through a calculation	A | B | C | D | F	
Use a protractor to accurately measure angles and associated error	A | B | C | D | F	
Apply angle measurements to the geographic coordinate system to describe, in a geologist format, the orientation of a line on Earth's surface relative to north or south	A | B | C | D | F	
Convert units for distance, time, and angles while maintaining correct precision.	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Measurements Practice Sheet

Remember – the exam questions come directly from the labs, so to do well on the exam, be sure to study ALL the questions on the labs and be able to correctly answer them on the exam. To assist, this study sheet gives you a chance to practice SOME of the skills from the first labs. BE CAREFUL – just because a question appears on this sheet doesn't mean it will show up on the exam. AND if it doesn't show up here, that doesn't mean that it WILL show up on the exam. Just like on the exam, **show ALL work.** (You may use a calculator.)

1. Use symbols and variable X to describe a measurement between 1 and 7 cm.	***2.*** Use symbols and variable X to describe a measurement that is greater than 4 m.
3. Round 45,325 to the tens precision	4. Round 3.6258 to three decimal places precision
5. The measured number, 1.7 cm, is precise to one decimal place and represents what range?	6. The measured number, 3220 cm, is precise to the tens and represents what range?
7. 1.7 cm ÷ 3 =	8. 3220 cm ÷ 3 =
9. 6.555 cm + 1.12 cm =	10. 56.5 cm – 1 cm =
11. 10 cm + 1 cm =	12. 12.7 cm x 8 =

1 mi = 5280 ft	1 in = 2.54 cm	1 km = 1000 m	1 g = 0.035 oz	1 cm/yr = 10 km/my
1 ft = 12 in	1 km = 0.6214 mi	1 m = 100 cm	1 kg = 2.205 lbs	1 km/hr = 0.2778 m/s

13. Convert 12.6 lbs to kg. (Show ALL work, with units – like one of the examples above

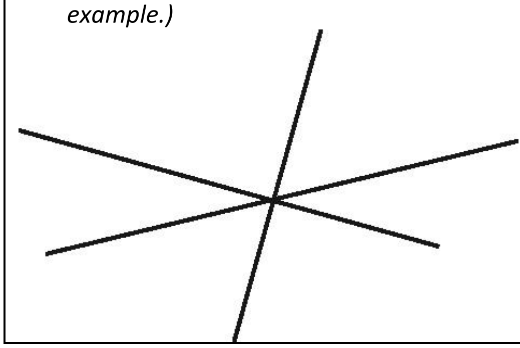
14. Convert 12 inches to centimeters. Show ALL work, with units – like one of the examples above

15. Convert 6.72 miles to feet. (Use ranges to determine rounding.) **Careful with rounding here!**

16. Convert 129 km/my to cm/yr. (Use ranges to determine rounding.) **Careful with rounding here!**

17. 42.125° = _________° _______’ _______”	18. 21°53’39” – 1°15’49” =

19. What is the orientation of these lines, according to **geologists**? (You can draw your own circle if helpful.) *(See example.)*



KEY

1. Use symbols and variable X to describe a measurement between 1 and 7. ***1<X<7 cm***	***2.*** Use symbols and variable X to describe a measurement that is greater than 4. ***X>4 m***
3. Round 45,325 to the tens precision ***45,330***	4. Round 3.6258 to three decimal places precision ***3.626***
5. The measured number, 1.7 cm, is precise to one decimal place and represents what range? ***1.65 to 1.74 cm***	6. The measured number, 3220 cm, is precise to the tens and represents what range? ***3215 to 3224 cm***
7. 1.7 cm ÷ 3 = ***0.6 cm***	8. 3220 cm ÷ 3 = ***1073.3 = 1070 cm***
9. 6.555 cm + 1.12 cm = ***7.68 cm***	10. 56.5 cm – 1 cm = ***55.5 = 56 cm***
11. 10 cm + 1 cm = 11 cm = ***10 cm***	12. 12.7 cm x 8 = ***101.6 cm***

1 mi = 5280 ft	1 in = 2.54 cm	1 km = 1000 m	1 g = 0.035 oz	1 cm/yr = 10 km/my
1 ft = 12 in	1 km = 0.6214 mi	1 m = 100 cm	1 kg = 2.205 lbs	1 km/hr = 0.2778 m/s

13. Convert 12.6 lbs to kg. (Show ALL work, with units – like one of the examples above
12.6 lbs x 1 kg/2.205 lbs = 5.7 kg

14. Convert 12 inches to centimeters. Show ALL work, with units – like one of the examples above
12 inches x 2.54 cm/1 inch = 30 cm

15. Convert 6.72 miles to feet. (Use ranges to determine rounding.) **<u>Careful with rounding here!</u>**
6.72 miles x 5280 ft/mile = 35,481.6 ft 6.715 miles x 5280 ft/mile = 35,455.2 ft 6.724 miles x 5280 ft/mile = 35,502.72 ft
So the range is between 35,455.2 and 35,502.72 (the hundreds place is the first to change; round to this):
ANSWER 35,500 ft

16. Convert 129 km/my to cm/yr. (Use ranges to determine rounding.) **<u>Careful with rounding here!</u>**
129 km/my x 1 cm/yr / 10km/my = 12.9 cm/yr
129.4 km/my x 1 cm/yr / 10km/my = 12.94 cm/yr
128.5 km/my x 1 cm/yr / 10km/my = 12.85 cm/yr ANSWER: 12.9 cm/yr

17. 42.125° = ___***42***______° ____***7***___' ____***30***___"	18. 21°53'39" – 1°15'49" = ***20°37'50"***

19. What is the orientation of these lines, according to **geologists**? (You can draw your own circle if helpful.) *(See example.)* ***N75W+/-2°, N15E+/-2°, N75E+/-2°***

Latitude and Longitude and Compasses

NEEDED SUPPLIES:

- Desktop version of Google Earth (download if you haven't already)
- Protractor to measure angles
- Compass (from hardware store – physical, OR phone app)
- Blank paper to use as a paper ruler
- Pencil and eraser

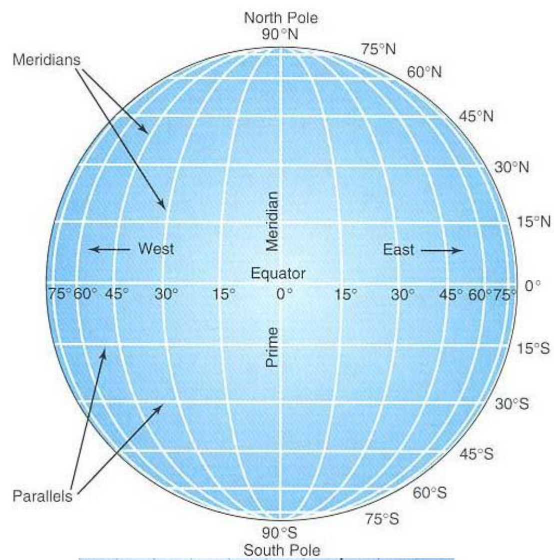
Latitude and longitude

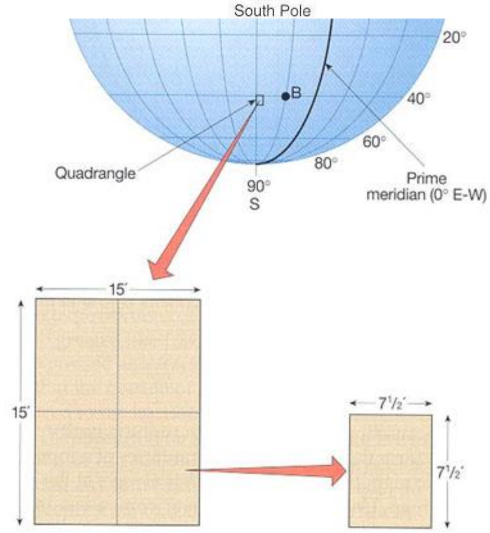
By international agreement the earth's surface is divided by a series of east-west and north-south lines to form a grid. If the earth's surface were flat, it would be easy to set up a global grid system. Simply designate some point as the starting place (origin) and measure your distance east or west (right or left on a map) and north or south (up or down on a map) relative to the origin. But the earth's surface is circular, so we must do something slightly more complicated. Instead of measuring miles or inches up and down and right and left from the origin, we measure angles (degrees). There are 360 degrees (°) in a full circle, 60 minutes (') in one degree, and 60 seconds ('') in one minute. These minutes and seconds are units of angle and have nothing to do with time. We use the intersection of the **equator** (imaginary line running around the center of the planet) and **prime meridian** (imaginary line connecting the poles and intersecting Greenwich, England) as the origin. So we can describe each surface position in degrees north or south of the equator (90° north and south are the maximums) and degrees east or west of the prime meridian (180° east and west are the maximums).

- **Parallels** (lines of **latitude**) circle the globe parallel to the equator. Latitude is measured from the equator to 90° N at the North Pole and 90° S at the South Pole.
- **Meridians** (lines of **longitude**) are north-south lines that run from pole to pole. Meridians are measured east and west of the prime meridian to 180°, which is the **International Date Line**.

Most maps are based on latitude and longitude: their east and west boundaries are meridians and their north and south boundaries are parallels. The United States Geological Survey (USGS) currently produces only 7.5-minute (1/8°) quadrangles, which means that there are 7 ½ minutes of latitude between the north and south boundaries and 7 ½ minutes of longitude between the east and west boundaries. When near the poles, such maps are significantly narrower than they are tall: the east-west distance across the map is less than the north-south distance even though the map encompasses the same amount of latitude and longitude. When near the equator, they are squarer.

{One 15' quad is 15' of latitude by 15' of longitude. There are four 7.5' quadrangle maps in each 15' quadrangle map.}

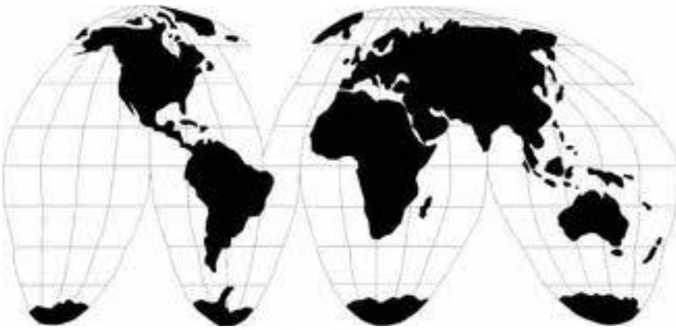




Images: Top – Unknown source. Bottom – USGS.

MAPS IN GENERAL

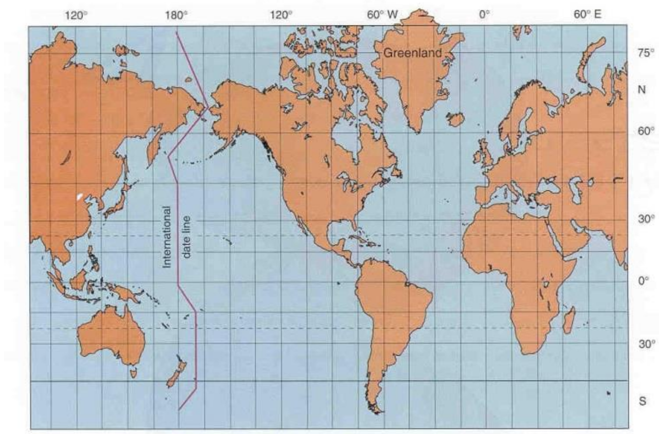
Map making on a global scale is a series of clever compromises to do a good job showing a spherical surface on flat paper. The only truly accurate map is a globe. All other maps have inherent distortions.



(Image: public domain)

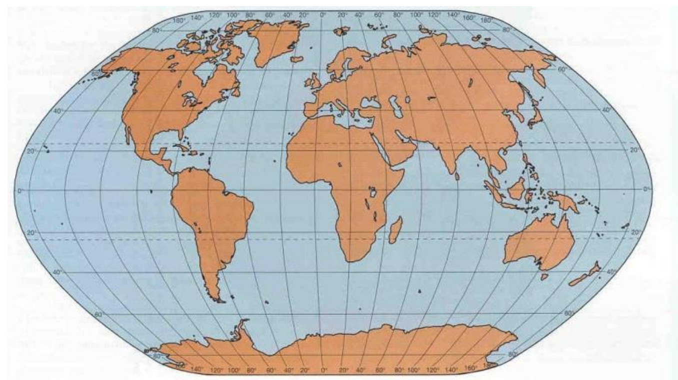
Goode's homolosine projection.

The obvious problem with this projection is that adjacent areas in some parts of the world are depicted as being widely separated. The Goode's projection in particular cuts the continents and so shows the three oceans to best advantage. Note that the meridians of longitude converge to points, thus not distorting the shapes and sizes of high-latitude areas. Areas on this map are equal.



(Image: unknown source)

Mercator projection. Shapes are similar to globe, but areas are distorted, appearing wider as you move away from the equator. South America is really 9x bigger than Greenland. Does it look that way here?



(Image: unknown source)

Hoelzel projection. Note that the meridians of longitude converge to a line shorter than the equator but still not a point. Thus polar areas are more distorted than equatorial areas, but not as much as in Mercator projections.

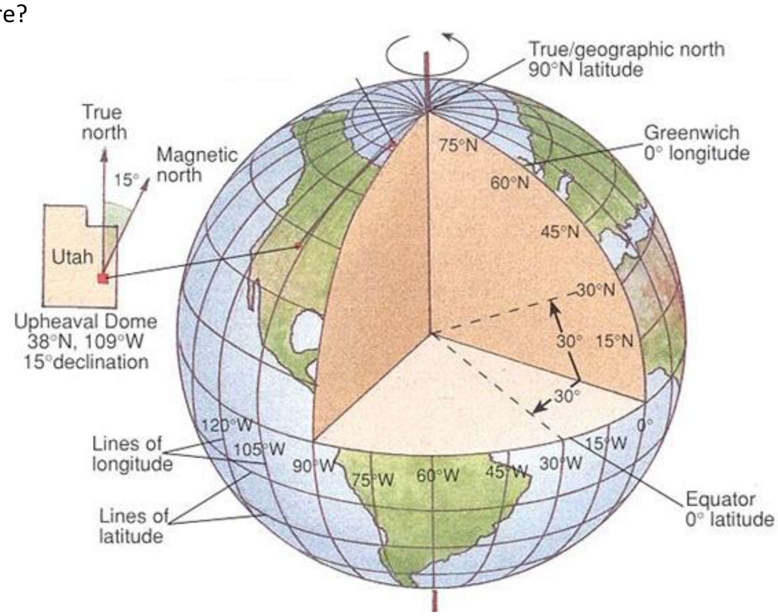


Image: USGS 1980s

Orientation

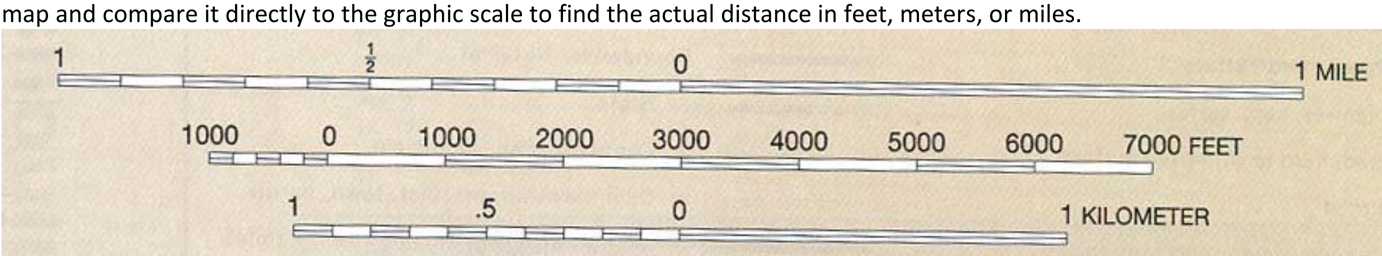
All U.S.G.S topographic maps and most other maps are made with north at the top of the sheet. True north is the direction to the north geographic pole (true north – designated as TN or *). The north-seeking end of a compass needle is attracted to Earth's north geomagnetic pole, which in 2017 was at **86° 30' N and 172° 36' W (86.5, 172.6).** Each topographic map has two north arrows in the lower margin, indicating the directions of both true north and magnetic north. The angular difference between these two directions is called the **magnetic declination**. In the image above, the magnetic declination at Upheaval Dome, Utah in the 1980s was N15°E.

Scale

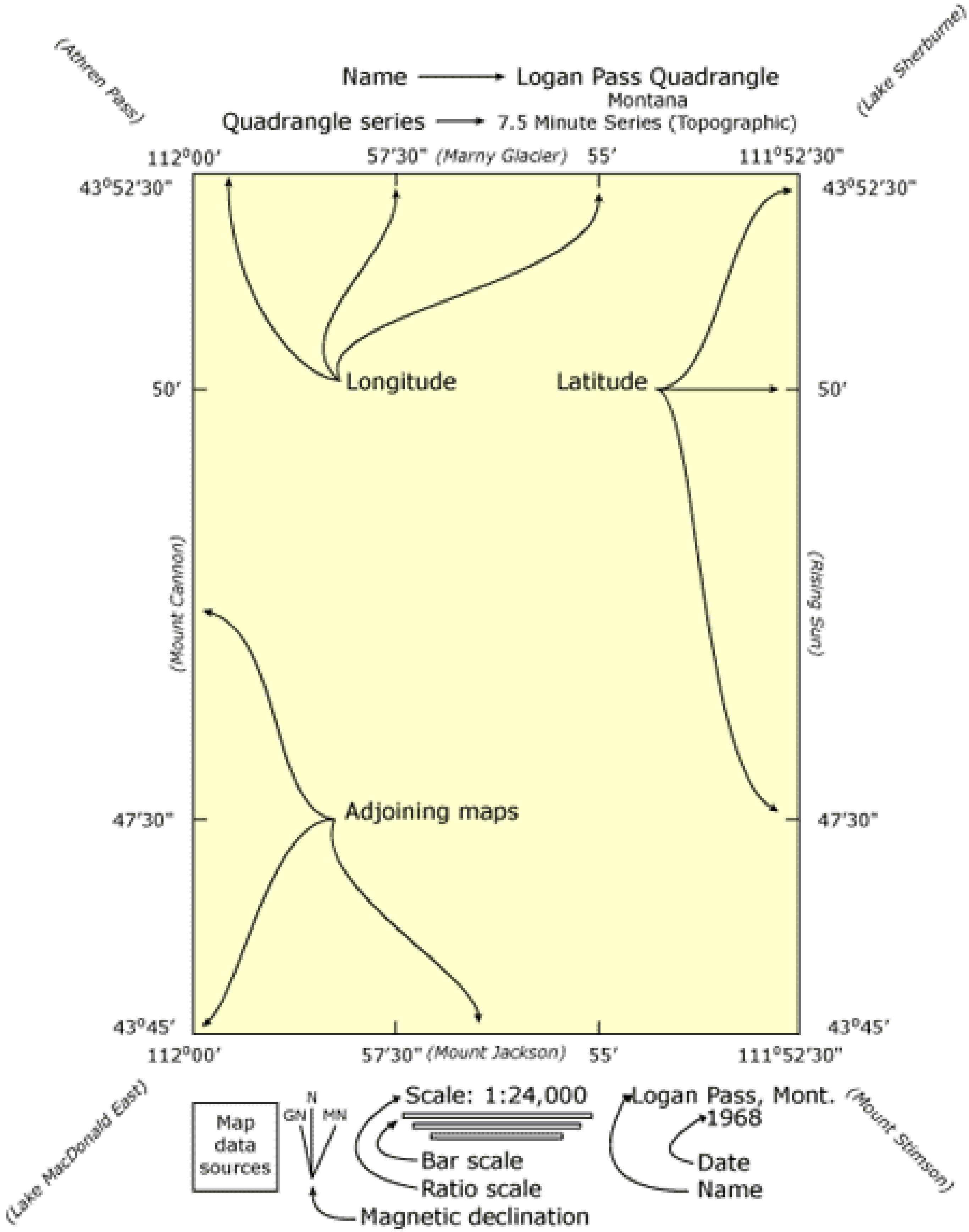
The scale of a map is the ratio of a given distance on the map to the corresponding distance on the ground. It may be expressed fractionally, verbally, or graphically. Fractional and graphical scales can be found in the center of the lower margin on all standard U.S.G.S. quadrangles. The fractional scale is a ratio of equal units (inches, feet, yards, meters, etc.). One commonly used scale is 1:62,500. This means that one inch on the map represents 62,500 inches on the ground, or one centimeter on the map represents 62,500 centimeters on the ground. Verbal scales appear as words at the bottom of the map. Commonly used fractional scales and the corresponding verbal scales are given in the following table. *Note: Larger-scale maps show a smaller area, but in greater detail. Small-scale maps show little detail, but a large area.*

	Fractional scale	Verbal scale	Examples of maps using each scale
Largest scale	1:24,000	Approximately 2000 feet per inch	7.5-minute quadrangles
	1:62,500	Approximately 1 miles per inch	15-minute quadrangles
	1:125,000	Approximately 2 miles per inch	30-minute quadrangles
	1:250,000	Approximately 4 miles per inch	60-minute quadrangles
	1:500,000	Approximately 8 miles per inch	Many state maps
Smallest Scale	1:1,000,000	Approximately 16 miles per inch	
	1:2,500,000	Approximately 40 miles per inch	Geologic map of the United States

The bar that looks like a ruler in the center of the lower margin is the graphic scale. It is easy to pick a distance from the map and compare it directly to the graphic scale to find the actual distance in feet, meters, or miles.



Scale bar. Notice that the ZERO mark is in the center, and the left side includes detailed subdivisions. Image: USGS



Sample USGS Quadrangle. Note: MN = Magnetic North | N = True North | GN = Grid North (military use)

Using Google Earth/Oceans – The Basics

To go to a particular location within Google Earth, enter latitude and longitude as follows:

- Latitude first, Longitude second.
- Put spaces between degrees, seconds, minutes (and don't include the units)
- Positive latitudes are North, Negative are South
- Positive longitudes are East, Negative are West
- Example: 46° 23' 15" N, 122° 22' 15" W is entered as: 46 23 15 -122 22 15
- If you enter decimals, Google Earth/Oceans interprets it as a fraction of a degree. Example: 23.5 = 23° 30' 00"

To find the latitude and longitude of a particular location in Google Earth/Oceans, you can drop a pin and look at its properties, or you can hold the cursor over the location.

Google Earth provides all latitudes and longitudes with the letter/direction first. Please convert those to correct format before recording in lab. Example: N 20° 15' 43" should be written as 20° 15' 43" N.

To measure distance and orientation in Google Earth/Oceans, use the ruler tool as follows:

- Locate the ruler icon at top of map
- Use the drop-down menu to choose your units (kilometers is preferred!)
- Click on your starting location and then click on your end location.
- Read answers for distance and orientation of that line (note that it's important you start on right side for orientation).

Google Earth provides all orientations as "heading" in the ruler tool and provides the answer in a modified Oceanographer format. It adds a letter afterwards. Be sure you convert those numbers to the correct format. Example: 220°W should first just be 220° (Oceanographers) or S40°W (Geologist's format). For a review on formats, return to Measurements Lab.

Latitude, Longitude, & Compasses Prereading Homework

Use your own words in your answers – NOT verbatim from the prereading material.

1. How many minutes in a degree? (‘ in a °)	2. How many seconds in a minute? (“ in a ‘)

3. What is wrong with maps that don’t show longitude lines converging at the poles? (Be specific.)

4. How does a 7.5’ map get its name? (Be specific – what does the map name mean?)

5. Which runs North-South? Latitude or longitude (Circle correct answer.)

6. Which runs East-West? Latitude or longitude (Circle correct answer.)

7. Which indicates location North-South? Latitude or longitude (Circle correct answer.)

8. Which indicates location East-West? Latitude or longitude (Circle correct answer.)

9. What is the **latitude** of each of the following?
   The equator The north pole The south pole

10. What is the **longitude** of each of the following?
    The prime meridian The international date line

Compasses

11. Looking at the website link to NOAA’s **Magnetic Pole Wandering**, find and provide below the latitude and longitude of magnetic north pole, then enter that into Google Earth (browser version or downloaded desktop version) and describe that location (is it on an island or continent? In the ocean?)

12. Looking at the website link to NOAA’s **Magnetic Declination Estimated Anywhere** website, what is the magnetic declination (magnetic north’s variation from true north) for San Francisco today? For Manila, in the Philippines? Give in the Geologist’s format for bearing.

13. Looking at the website link to NOAA’s **Magnetic Declination Estimated Anywhere** website, click on the U.S. Historic declination tab and look at how magnetic declination has varied in San Francisco since 2000. In just the last 20+ years, how much has magnetic declination varied?

Latitude, Longitude, & Compasses Lab Exercises

Google Earth & Google Oceans

Log on to the department laptops. Launch Google Earth & Oceans (desktop version – browser version can be used in a pinch, but need to have access to ruler tool). Explore a bit. You'll be using this software throughout the semester. But you'll be learning it from each other and from the software itself. Be patient. If you have questions, ask.

- **Latitude & Longitude:**
  - To determine latitude and longitude:
    - Turn on grid lines (these are latitudes and longitudes).
    - Or click on a point and look at the lat/long shown in the lower right corner.
  - Google Earth can search on latitudes and longitudes, but you must enter them like this: 37 30 15, 122 45 13 (where the first set of numbers are latitude in degrees, minutes, and seconds, and the second set of numbers is longitude in degrees, minutes, and seconds; positive latitudes are N of the equator; negative latitudes are S of the equator; positive longitudes are east of the prime meridian; negative longitudes are west of the prime meridian.)
- **Distance and Orientation:** use the ruler to measure distance and orientation—from first click toward second click; orientation will be given using the Oceanographer's standard: 0-360 measured clockwise from north; be sure you understand how that relates to your geologic orientations).

Latitude and Longitude estimates using Google Earth

	Grid Lines	Click on point
1. What is the latitude and longitude of **San Francisco**? *(Be sure to provide direction and the error range based on the precision of you and your instrument.)*		
2. What is the latitude and longitude of **Sydney, Australia**? *(Be sure to provide direction and the error range based on the precision of you and your instrument.)*		
3. All of the above measurements have an error associated with them. What factors were involved in calculating your error for each?		

Distance and Orientation

4. What is the distance between New York and London **in kilometers**? (Don't forget units!) *(Be sure to provide the error range based on the precision of you and your instrument.)*
5. What is the orientation of the line drawn FROM New York TO London? (Don't forget to use proper formatting!) *(Be sure to provide the error range based on the precision of you and your instrument.)*
6. List two small, unique places that the International dateline passes through.
7. List two small, unique places that the Prime Meridian passes through.
8. List two small, unique places that the Equator passes through.

San Francisco South Quadrangle *(paper copy or digital version linked on class website)*

Look at the San Francisco South quadrangle topographic map. Note that there are two sets of numbers on the edges of the chart. The black numbers that appear most frequently are kilometers away from a grid origin used by the military. Ignore those. Instead, look for the longitude and latitude measurements. You can find them on all corners, and usually 2-4 more evenly spread across each map edge.

9.	What are the latitudes of the north and south boundaries of the map respectively?
10.	What are the longitudes of the west and east boundaries of the map respectively?
11.	How much angle of latitude is covered by this map?
12.	How much angle of longitude is covered by this map?
13.	What size map is this (in minutes)?
14.	What is the fractional scale of this map?
15.	What is the verbal scale of this map? (This information is not usually on the map. See table in prereading for answer.)
16.	What was the magnetic declination in this quadrangle when it was made (and when was that)? (Format answer correctly for orientations!)
17.	Comparing the above answer to the one you got in the prereading, how much has magnetic declination changed in San Francisco since this map was made?
18.	Locate City College Ocean Avenue Campus and using the map only *estimate* its present latitude and longitude to the nearest second with error.
19.	What is your answer to the above from Google Earth (with error)? (Is your Google Earth measurement within the error of your estimate from the map (previous question)?)
20.	Notice that the above map is longer from bottom to top than from right to left, even though the area encompasses the same number of degrees of latitude (north-south) and longitude (east-west). Also note that the east and west boundaries of the map should not be parallel to each other. Explain why.

Mono Craters Quadrangle *(paper copy or digital version linked on class website)*

21. What is the quadrangle size in minutes?	22. What was the magnetic declination in this area when the map was made and when was that?

**For Google Earth, you might need to search by sight, not on name, because there are many similarly named locations.*		
	ANSWER USING MAP	**ANSWER USING GOOGLE EARTH**
23. Accurately describe the location of **Crater Mountain** with latitude and longitude to nearest second. Provide error range.		
24. Locate **Punch Bowl** by giving its latitude and longitude to the nearest second. Provide error range.		
25. How far is it, as the crow flies, between Crater Mountain and Punch Bowl? (in kilometers) Provide error range.		
26. What is the orientation of the line that connects the two? (Use the standard for lines with no arrows.) Provide error range.		

Mt Whitney Quadrangle *(paper copy or digital version linked on class website)*

27. What is the quadrangle size in minutes?	28. What was the magnetic declination in this area when the map was made and when was that?

Orientation & Compasses

The **Brunton compass** has a two rings on the outside. The outer one goes from 0 to 360 and represents oceanographic standards for determining bearings and directional orientations (where 0 is north, 90 is E, 180 is S, 270 is W). The inner ring indicates N, S, E, W and has angle measurements from 0 to 90 and represents geologic standards for determining orientations (as learned in the last lab). The markings on the compass appear reversed from what you would think, so that the compass will give you the correct reading when you face one direction and the internal magnet continues to point north. The inside of the compass (the face) is used for measuring dip, which we will do later in this class. Whether you use a Brunton compass or a more traditional mariner's compass, you have to correct it for the magnetic declination in your area. (*If you're doing this exercise at home, use a downloaded compass app on your phone or a compass you have purchased at a sporting goods store. (If you use a compass app on your phone, you can go into settings to set it to point to True North instead of Magnetic North. Otherwise, you should assume it's pointing at the magnetic north pole NOT the true north pole.)*

29. Get a compass and ensure it is corrected for the magnetic declination that you calculated in the prereading (or be aware it's not corrected, and make adjustments as needed). Go outside behind the lab (the metal in the lab tables interfere with compasses in class), or outside your house if you're at home. Stand just a few feet outside the door. Orient yourself by finding North, East, South, and West. What buildings or objects do you see in those directions?			
North	East	South	West

30. **Estimate first with no compass**, your bearing if you are facing the door you exited from the building. Indicate value using a geologist's standard. Then use compass to take more precise measurement. Provide error range. How good was your estimation?	31. **Turn your back to the door, and estimate first with no compass**, your bearing if you are facing away from the door you exited from the building. Indicate value using a geologist's standard. Then use compass to take more precise measurement. Provide error range. How good was your estimation?

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Use latitude and longitude to accurately describe with associated error (depending on instrument) a particular location on Earth's surface (using both maps and Google Earth)	A | B | C | D | F	
Use map information to evaluate magnetic declination in a particular region and how it will impact compass measurements	A | B | C | D | F	
Use a hand-held compass to accurately measure orientation of a line between two points on Earth's surface	A | B | C | D | F	
Measure distances and orientation angles between two objects on maps and provide accurate answer with appropriate error (using both maps and Google Earth)	A | B | C | D | F	
Use latitude and longitude to accurately describe with associated error (depending on instrument) a particular location on Earth's surface (using both maps and Google Earth)	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Latitude, Longitude, & Compasses Practice Sheet

Remember – the exam questions come directly from the labs, so to do well on the exam, be sure to study ALL the questions on the labs and be able to correctly answer them on the exam. To assist, this study sheet gives you a chance to practice SOME of the skills from the first labs. BE CAREFUL – just because a question appears on this sheet doesn't mean it will show up on the exam. AND if it doesn't show up here, that doesn't mean that it WILL show up on the exam. Just like on the exam, **show ALL work.** (You may use a calculator.)

1. Use this globe to define a 15' quad and to explain how a 15' quad's shape differs at the equator and at the poles.

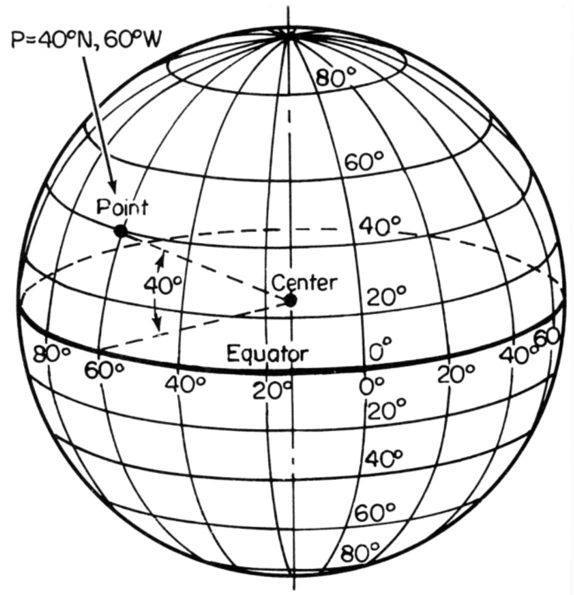


Image from US Department of Energy

2. Use the above globe and the Mercator projection to the right to explain what is wrong with flat maps of the world.

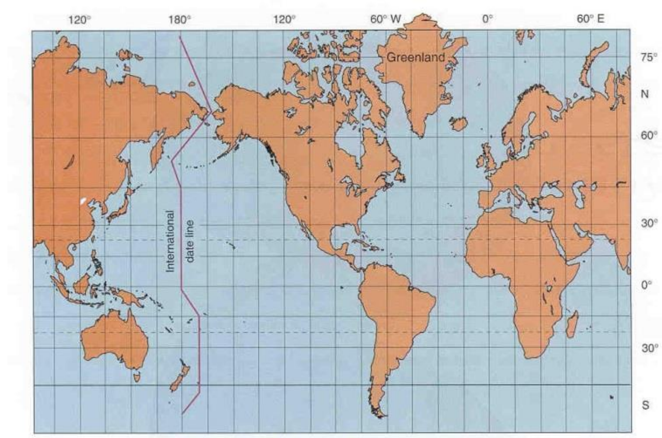


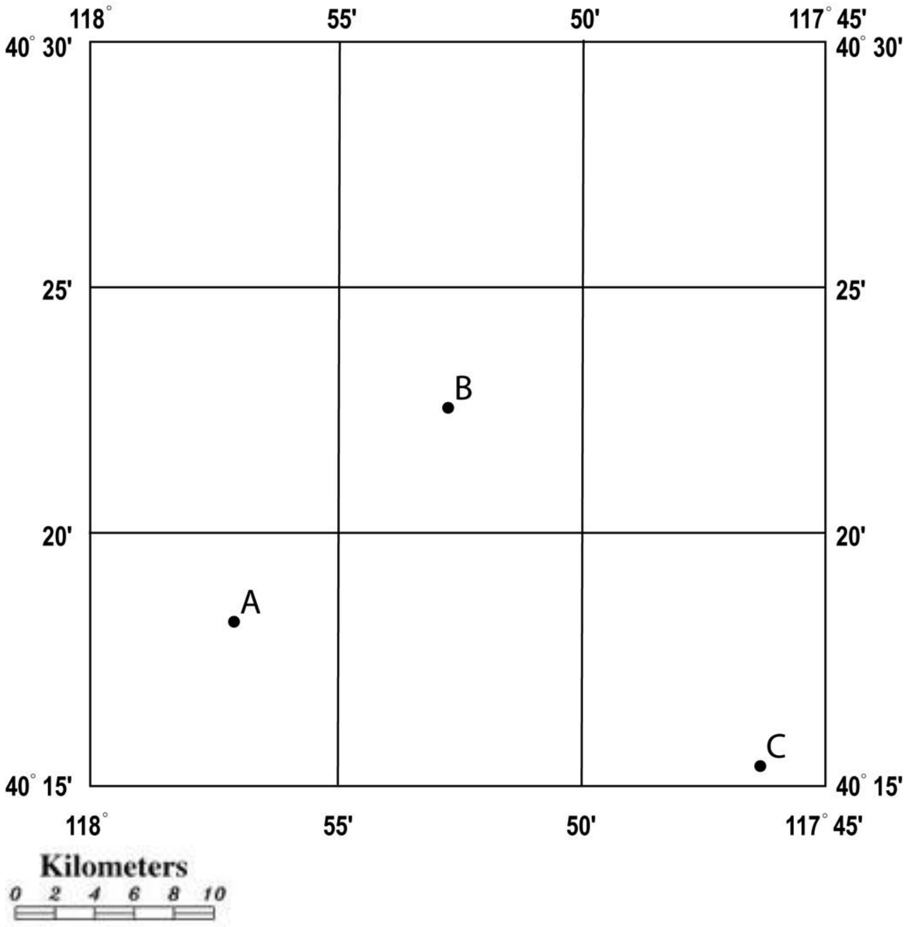
Image: Unknown

3. Earth's north geomagnetic pole in 2017 was at **86° 30' N and 172° 36' W** (86.5, 172.6). Open Google Earth and mark this location. Then enter the coordinates of location X = 89° 50'N and 82°E. I also recommend you find the North Rotational pole (90, any number for longitude). Put markers on all those locations. Use the ruler to draw a line from location X to the magnetic north pole. What is the orientation of this line (magnetic declination)?

4. What is the latitude and longitude of the southern tip of Africa?

5. What would magnetic declination be in Barrow, Alaska (again use Google Earth)?

6. Be sure you can use a compass to determine directions and orientations.



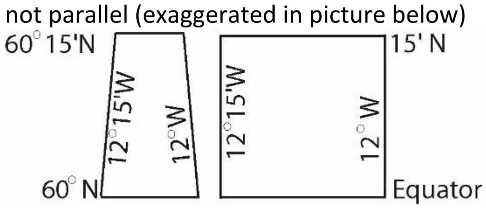
Latitude and Longitude

7. What is the latitude and longitude of point A?
8. What is the latitude and longitude of point B?
9. What is the latitude and longitude of point C?
10. What is the distance as the crow flies between Point A and C?

KEY

1. Use this globe to define a 15’ quad and to explain how a 15’ quad’s shape differs at the equator and at the poles.

   A 15’ quad has 15’ of latitude between the north and south boundaries and 15’ of longitude between east and west boundaries. On the globe, that shape is square at the equator (where latitude and longitude cover equal distances). But since longitude lines converge at the poles, there will be progressively less and less distance between them as you move north and south of the equator, while latitude still maintains the same distance. Maps towards the poles thus get narrower and are rectangles, as tall as the equator maps, but skinnier, and with right and left margins converging a bit – not parallel (exaggerated in picture below)



2. Use the above globe and the Mercator projection to the right to explain what is wrong with flat maps of the world.

   When the longitude lines are spread out at the north and south poles to make a flat map like this one, it stretches everything out – including the North POINT which is now a broad swath. As a result, all objects are stretched, to an increasing degree the further north and south you move from the equator.

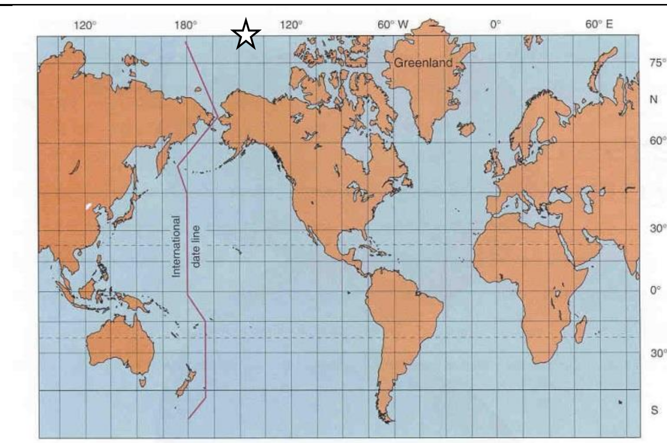


Image: source unknown

3. Earth's north geomagnetic pole in 2017 was at **86° 30' N and 172° 36’ W** (86.5, 172.6). Open Google Earth and mark this location. Then enter the coordinates of location X = 89° 50'N and 82°E. I also recommend you find the North Rotational pole (90, any number for longitude). Put markers on all those locations. Use the ruler to draw a line from location X to the magnetic north pole. What is the orientation of this line (magnetic declination)?
   ~N89E +/- 10°

4. What is the latitude and longitude of the southern tip of Africa? ***35+/-1°S 20+/-1°E***

5. What would magnetic declination be in Barrow, Alaska (again use Google Earth)? ***N3W +/- 2°***

6. Be sure you can use a compass to determine directions and orientations.

Latitude and Longitude

7. What is the latitude and longitude of point A.
   40°18’15”N 117°57’05”W +/-30”

8. What is the latitude and longitude of point B.
   40°22’30”N 117°52’35”W +/-30”

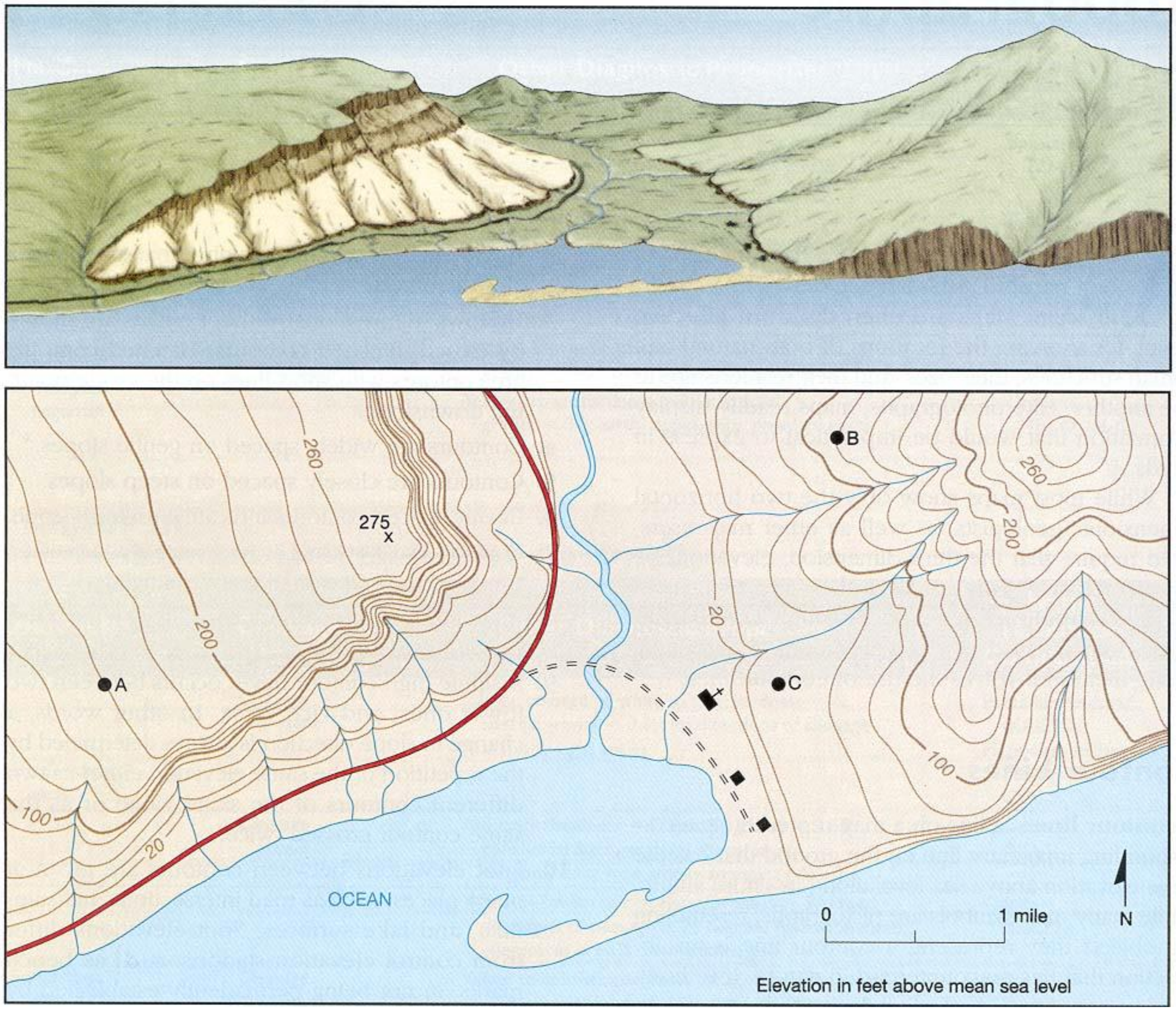
9. What is the latitude and longitude of point C.
   40°15’20”N 117°46’20”W +/-30”

10. What is the distance as the crow flies between Point A and C?
    27 km +/- 1km

Topographic Maps

NEEDED SUPPLIES:

- **Graph paper**
- Desktop version of Google Earth (download if you haven't already)
- Protractor to measure angles
- Blank paper to use as a paper ruler
- Pencil and eraser



Contour Interval: 20 feet (image: USGS)

Topographic maps show roads and cities, but in addition, they show elevation, so that readers can visualize the shape of the land surface in three dimensions. Geologists use topographic maps to locate themselves precisely in three dimensions (east-west; north-south; and elevation). Field geologists overlay topographic maps with geologic information discovered in the field to create geologic maps (future lab). It is equally important that anyone traveling in remote mountain or desert areas be able to read topographic maps. Imagine planning a hike between two parking lots separated on a road map by 1 mile. A topographic map shows the terrain between the two lots – important if there are ravines or mountains!

The U.S.G.S. has been commissioned by Congress to make a topographic map of the United States. The job was started in the late 19th century and is still in progress.

Definitions

These are some common terms used in discussing and describing features on topographic maps.

- **Topography** is the configuration of the land surface.
- **The datum plane** is the zero reference level. For nearly all topographic maps, it is mean sea level.
- The **altitude** or **elevation** of a given point is the vertical distance from the datum plane to that point.
- **Relief** refers to the difference in elevation between the hilltops and valley floors.
- A **bench mark** is a point of known altitude and is usually designated on a map by the letters B.M., accompanied by a number giving the altitude at that point, rounded to the nearest foot.
- The **height** of a feature is the vertical distance above its surroundings. Example: if the top of a hill is at an elevation of 1555 ft, and the surrounding area is at an elevation of 1000 ft, the hill is 555 ft high.

Colors and symbols
Five colors are used on modern topographic maps, each with specific meanings as follows:

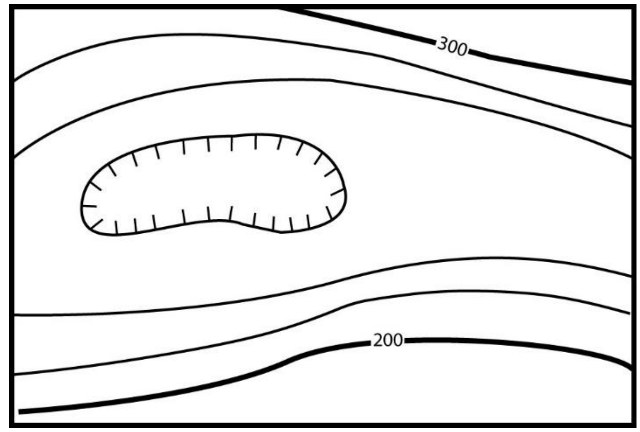
- **Black** is used for lettering, land boundaries, roads, cities, schools, buildings, etc.
- **Brown** is used for contour lines. Sand dunes, stream deposits, and some other clastic debris are shown by patterns of brown dots.
- **Blue** indicates water. Oceans, lakes, rivers, canals, and swamps are in blue. Intermittent streams or lakes are indicated by dashed or dotted lines and by patterns of blue lines. Blue contour lines are drawn over the surface of a glacier. These should not be mistaken for the decorative, blue lines drawn parallel to the coastline or around islands.
- **Green** indicates vegetation cover. This feature is optional on many quadrangle maps. For field work, maps without the green overlay are usually preferred.
- **Red** is used for major highways on modern maps. It is also used for section and township boundaries and section, township, and range numbers on 7.5-minute quadrangles.

Contour lines
Topographic maps are essential tools in geologic studies because they show the shape of the land surface in great detail. This is accomplished by means of carefully drawn contour lines, which connect points of the same elevation. Because the sea surface is (nearly) horizontal, you might think of contour lines as successive shore lines that would be made by the ocean if it were to rise and cover the land. The contour interval is the difference in elevation between one contour line and the next. The **contour interval** for a given map may be any value, commonly from 5 feet to 100 feet, depending on the scale and the steepness of the terrain. Some maps have two contour intervals, a small interval for flat or gently sloping ground, and a large interval for more rugged terrain.

The contour lines are based on surveyed elevations of key points in the area. The U.S. Coast and Geodetic Survey and the U.S. Geological Survey have set permanent brass, iron, and concrete markers as **bench marks** for use in surveying both horizontally and vertically. Bench marks are most commonly established at road intersections, on railroads, bridges, mountain tops, and other prominent locations and give the precise elevation (in feet) at that site. Therefore, at mountain tops it is common to see a numerical elevation value written at the top of a mountain peak that is greater than the topographic contour line below it but less than the next successive topographic line. For example, the topographic map on the previous page has a contour interval of 20 ft. and the high point in the region is 275 feet, which lies below 280 ft but above the 260 feet contour.

These miscellaneous facts should help you interpret the patterns made by contour lines.
- All contour lines close somewhere, although the closure point may not appear on a map sheet.
- Contour lines never cross one another, except where they represent overhanging cliffs; in that case, contours beneath the overhang are shown as dotted lines.
- Contour lines never divide or split, although they may appear to do so when they represent a vertical cliff. In this case they overlap one another.
- Contour lines are farther apart on gentle slopes and closer together on steep slopes.
- Contour lines bend (or V points) upslope for valleys or canyons and cross valley or canyon floors perpendicularly, making a V pointing upslope.
- Contour lines bend (or V points) downslope for ridges, which are linear sloping landforms that sit between two valleys or canyons as they cut through a mountain.
- Closed Contour lines represent hilltops or mountain tops.

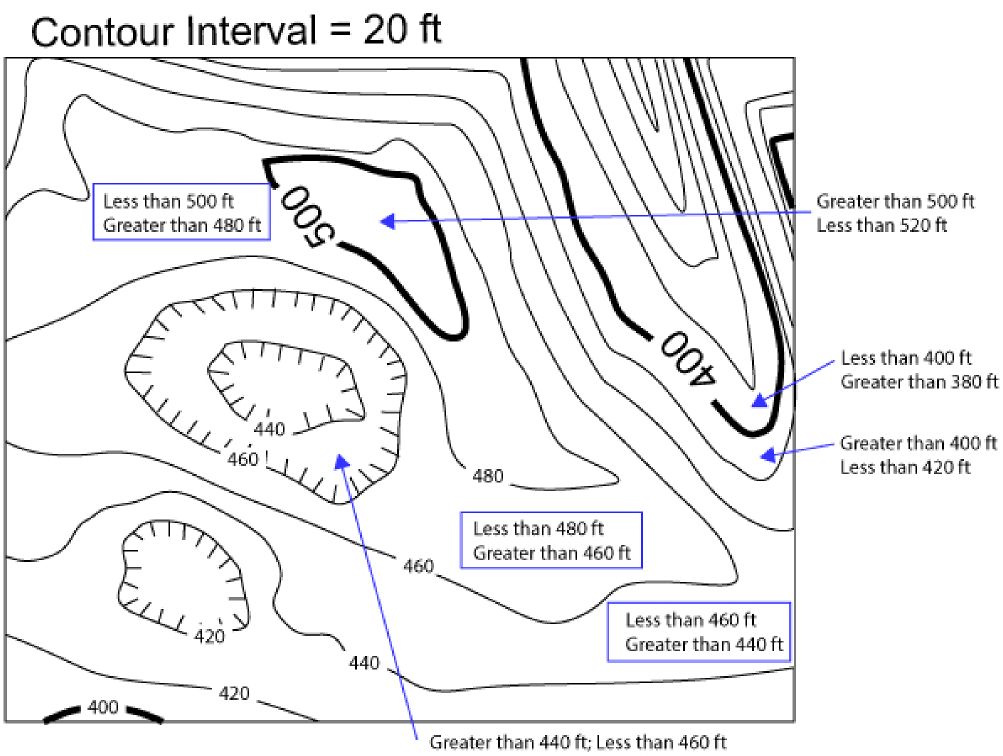
- Closed depressions (without outlets) are represented by closed contours with hachures (tick marks) on the inside, pointing down slope. (See image on next page.)
- Surveyed bench marks, many road intersections, mountain peaks, and other special points commonly have a printed elevation given opposite a cross, triangle, or other symbol.
- Every fourth or fifth contour line (depending on the contour interval) is called an **Index** contour and is printed heavier than the other lines. The elevation of the index contour is printed somewhere along the line. (See image on previous page.)
- Every map has the scale and the contour interval given in the center of the bottom margin.
- Blue contour lines are drawn over the surface of a glacier. These should not be mistaken for the decorative, blue lines drawn parallel to the coastline or around islands.



Contour Interval: 20 feet;
Image: D. DeVecchio –BY-NC-SA 3.0

Determining elevations

The elevation of a point is its vertical distance above sea level. Specific elevations are commonly given for town centers, hilltops, bottoms of depressions, road junctions, and index contours. ***Elevations between contours should NOT be interpolated. For example, elevation of a point midway between the 1240 and 1260-ft contours should be given as 1240 < X < 1260 ft.*** Approximations assume that slopes are straight between contour lines, which is rarely the case.

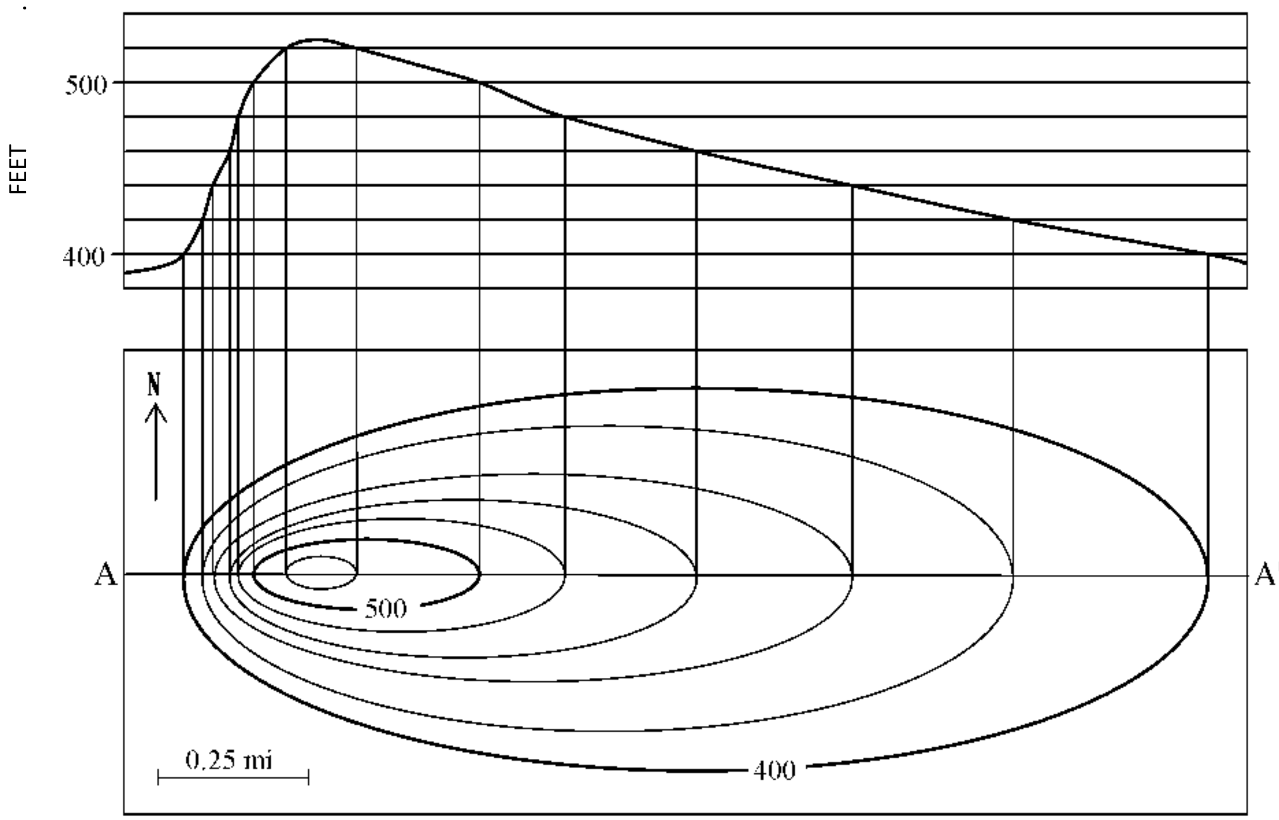


Topographic profiles

Topographic maps represent the land surface as seen from directly above. A topographic profile is a sideways view of the shape of the land surface (like cutting a donut in half and looking at its cross-section). Profiles are important for detailed studies of landforms and geology.

The vertical scale (Y-axis) of a profile may be exaggerated to emphasize landscape features. If the horizontal scale (X-axis) is 5000 ft per inch, and vertical features are plotted so that one inch represents 1000 ft, the vertical exaggeration is 5:1. For most purposes, including geologic cross-sections, vertical and horizontal scales should be the same. To construct an accurate profile along any straight line on the map:

1. Lay a strip of paper along the line across which the profile is to be constructed.
2. Use a sharp, reasonably hard pencil to mark on the paper the exact place where each contour, stream and hill top crosses the profile line. On steep slopes or on slopes of even gradient, you can get by with marking only the index contours.
3. Label each mark with the elevation that it represents, or indicate that it is a stream, hilltop, etc.
4. Prepare a vertical scale on a profile paper (such as a piece of graph paper) by labeling the elevations represented by horizontal lines.
5. Place the strip of paper on the profile paper. Project each contour to the horizontal line that represents that elevation, and mark it with a small dot.
6. Connect all points with a smooth line.
7. Copy the horizontal scale from the map to the X-axis of your profile.
8. Be sure your vertical scale has units.



Contour Interval: 20 feet

Creating a topographic cross-section. Image: Ralph Dawes and Cheryl Dawes – Creative Commons: CC BY 3.0 US

Calculating precision rounding for vertical exaggeration (REMINDER: 5280 ft = 1 mile)

Example for above graph:

Y axis: 1 inch = 100 ft; Precise to tens place. RANGE: 95 to 104 ft

X axis: 1 inch = 1/4 mile = 1320 ft; Infinitely precise, because it's the definition of the map scale

Vertical exaggeration = $\frac{1320 \text{ ft/in}}{100 \text{ ft/in}}$ = 13.2 times or 13:1

Range: $\frac{1320 \text{ ft/in}}{95 \text{ ft/in}}$ = 13.9 times $\frac{1320 \text{ ft/in}}{104 \text{ ft/in}}$ = 12.6 times The first digit to change is the ones place, so the exaggeration should be rounded to ones.

Answer: 13 times exaggeration!

Topographic Maps Prereading Homework

You will need graph paper for this lab. Please bring a few sheets with you to lab.

1. What is an index contour, and how do you recognize it?

2. If a hilltop is at 2400 ft. and the surrounding area is at 1300 ft, how high is the hill?

3. If one inch on the horizontal axis of a topographic profile = 1000 feet (precise to the hundreds), and 1 inch on the vertical axis = 50 feet (precise to the tens), what is the vertical exaggeration?

4. If you create a topographic profile with a vertical scale of 1 in = 20 feet (precise to the ones) and a horizontal scale of 1 in = 500 feet (precise to the tens), what is the vertical exaggeration?

5. In the prereading figure, describe the topography at point A (steep hill, gentle hill, flat plain, river valley, hilltop, saddle between hilltops, cliff, etc.) and provide elevation of point A.

6. In the prereading figure, describe the topography at point B (steep hill, gentle hill, flat plain, river valley, hilltop, saddle between hilltops, cliff, etc.) and provide elevation of point B.

7. In the prereading figure, describe the topography at point C (steep hill, gentle hill, flat plain, river valley, hilltop, saddle between hilltops, cliff, etc.) and provide elevation of point C. (Notice that this point is between two lines; do not estimate elevations; instead give a range, like $200 < x < 250$ ft.)

8. **Topographic Profile**: Draw a topographic profile between A and B for the first figure of the prereading (use graph paper and attach to back of this sheet; be precise).

9. What is the vertical exaggeration of the profile you just drew? SHOW WORK.

Topographic Maps Lab Exercises

MODELS *(At home, review the video on the website showing the different models.)*

	Each of the six models is approximately 8 in x 11 in. Each is accompanied by a corresponding topographic map *(digital versions on website).* Review each of the models. Use the models as references, to learn and confirm general rules, as you answer the following questions.
1.	The Models do not show hachure marks in the depressions (because they are incomplete). Which models have depressions and need hachure marks?
2.	Review the **hilltops** shown in the models. Notice what they all have in common – the common shape of a hilltop. In this space, sketch one example of a generic hilltop (use at least four contour lines) that is **very steep on the west, gentle on the east. Add north arrow to your drawing.** *Do not draw a copy of what is on the models – just use them as a guide.*
3.	Basic contour rules: **Steep slopes** are recognized how?
4.	Review the **stream valleys** shown in the models. Notice what they all have in common – the common shape of a stream valley. In this space, sketch one example of a stream valley (use at least four contour lines) that is **moving downstream from east (right side of paper) to the west (left side of paper). Add north arrow to your drawing.** *Do not draw a copy of what is on the models – just use them as a guide.*
5.	Basic contour rules: How can you tell **downhill direction of a stream valley**?
6.	On a sheet of unlined paper, draw a topographic map of a **perfect volcanic cone** (equal slopes on all sides) with a crater in the top. *(Use pencil; include at least ten contour lines, a North arrow, and a horizontal scale bar of 1 inch = 1 mile.)*
7.	Index contours are darker than the rest and represent a particular interval (4 or 5) of lines. For your drawing of a cone, assume that the contour interval is 20 feet. The index contours should mark every 100 feet. Assuming that the lowest contour line in your model is 280 feet, darken and label every index contour. (100 multiples only – so 280 is NOT an index contour.)
8.	What is the elevation of the highest point on your map? (Be as specific as you can! *Remember: We do not estimate elevations – if not on a line, give a range*.)
9.	What is the elevation of the center of the crater? (Be as specific as you can! *Remember: We do not estimate elevations – if not on a line, give a range*)
10.	Draw a profile line across your cratered dome from West to East and complete a topographic profile.
11.	What is the orientation of your profile line?
12.	What is the vertical exaggeration of your profile? (Show work.)

13. Compare the shape of the contour line patterns of the stream valleys in Models 1, 2, 3 to the glaciated valleys in Model 6. To understand better their differences, review the following-page maps of river and glaciated valleys, and draw two topographic profiles -- one across each valley. DRAW THESE PROFILES ON THE PAGE THAT FOLLOWS THE MAPS, not on your own graph paper).
14. What is the vertical exaggeration (horizontal scale / vertical scale) of these two profiles? Show work.

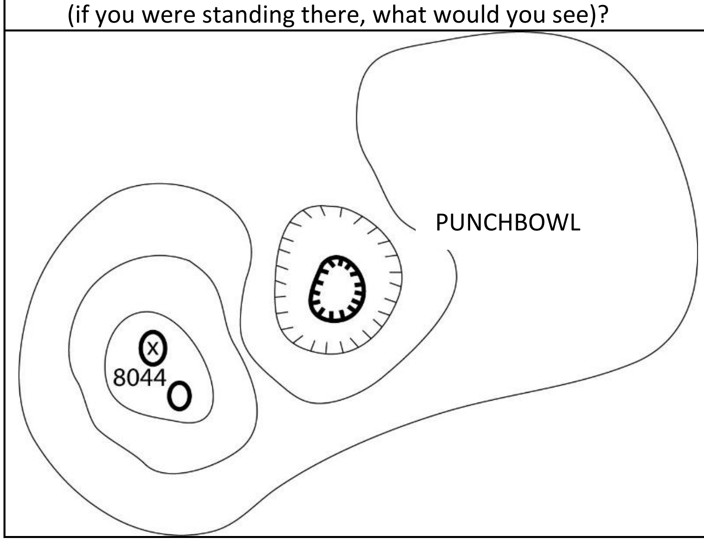
Mt. Whitney Quadrangle

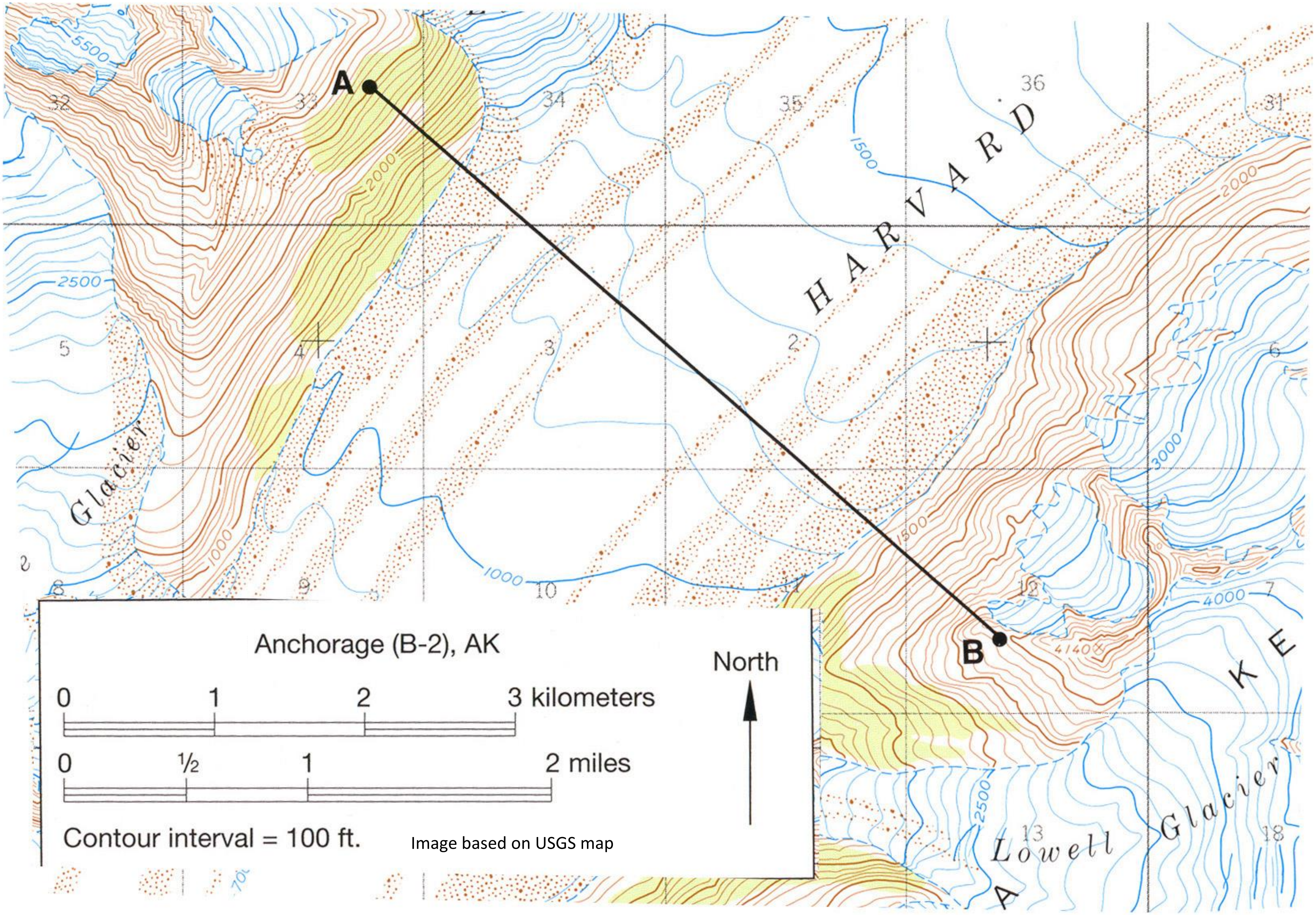
15. What is the contour interval of this map? (Don't forget units!)	16. What is the INDEX contour interval of this map?

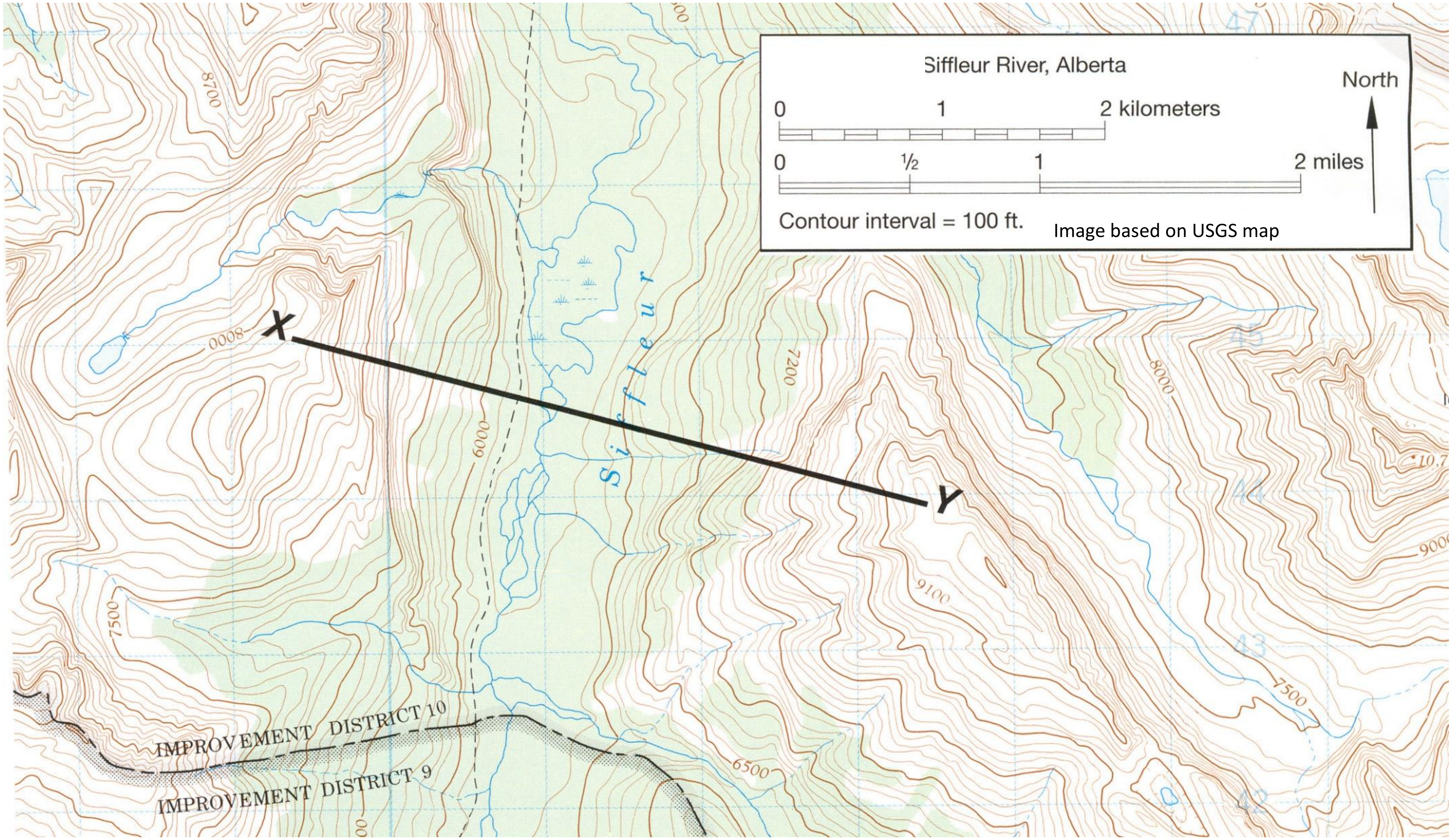
Find the elevation of each of these features in feet (don't forget to include units!)	
17. The bench mark in the town of Independence:	18. Owens Lake shore (no benchmark, be as precise as possible!):
19. The benchmark at the top of Mt. Whitney:	20. Manzanar (town) Benchmark
21. In Google Earth & Ocean, draw a path between Mt. Whitney and Manzanar. Save it. Go to Edit > Show Elevation Profile. Check your elevations with what you listed above. Are they close?	
22. In Google Earth & Ocean, draw a path between Highway 99 and Manzanar, through Mt. Whitney. Save it. Show Elevation Profile. Which is the steepest side in this cross-section (east or west)?	

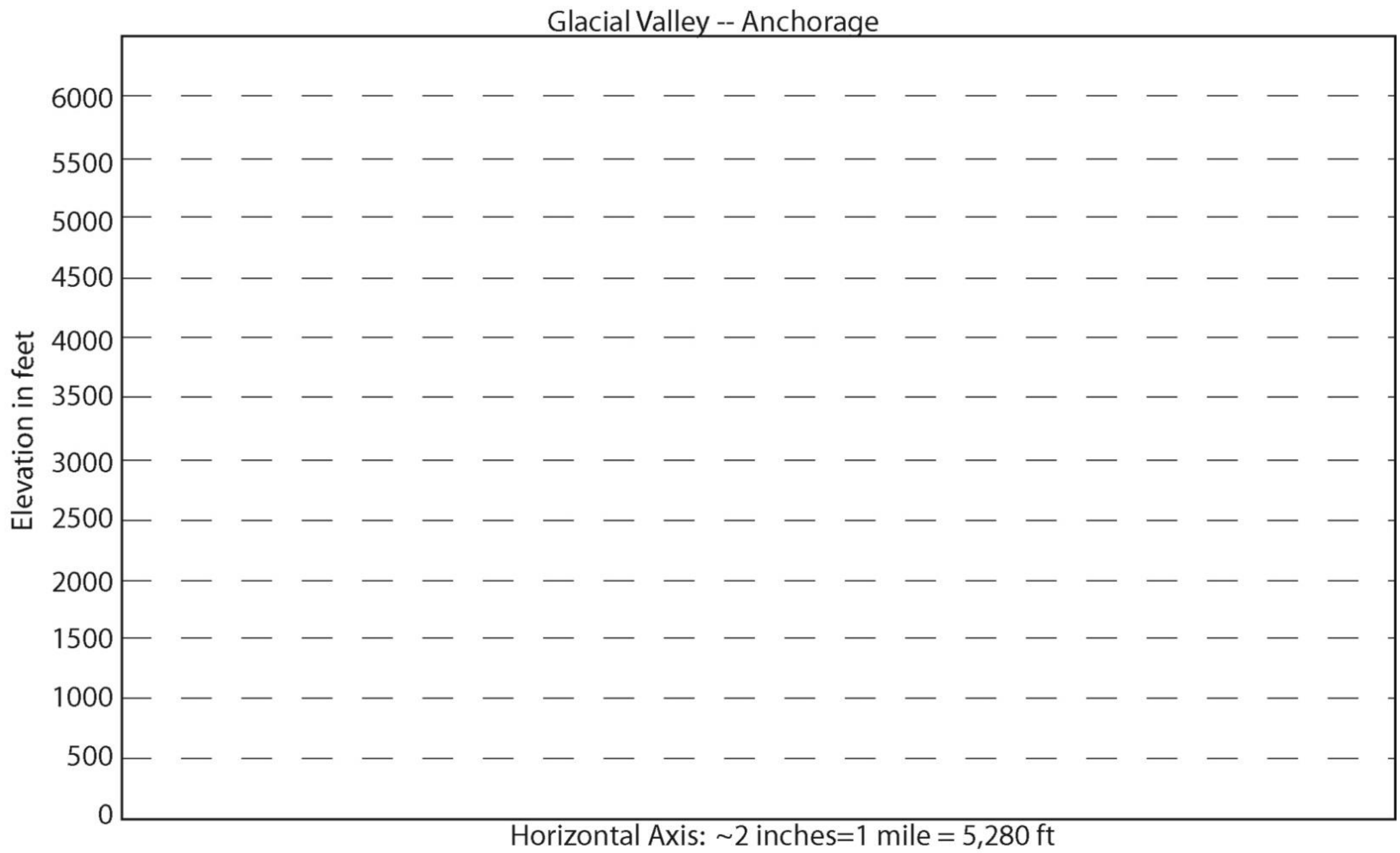
Mono Craters Quadrangle

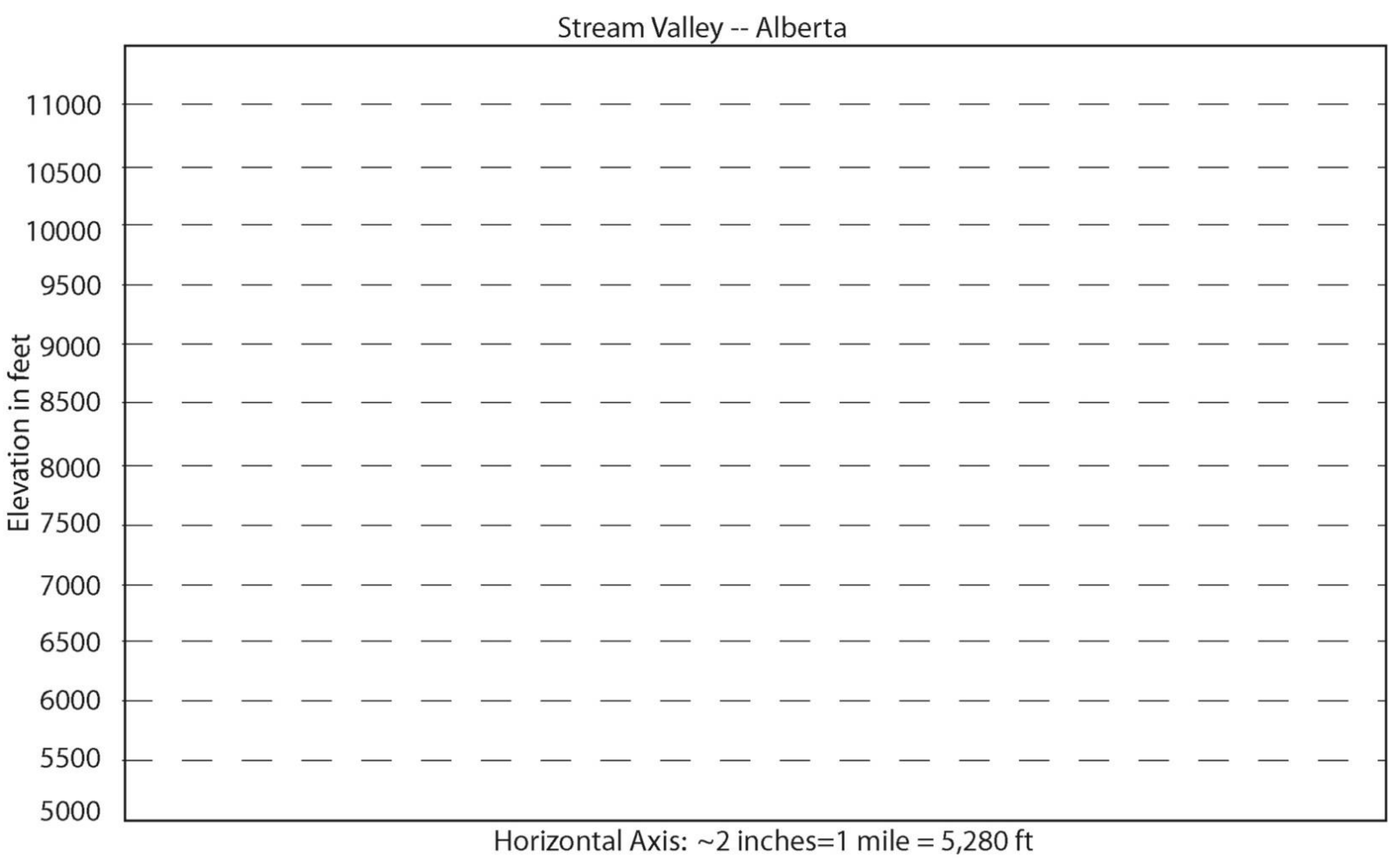
23. What is the contour interval of this map? (Don't forget units!)	24. What is the INDEX contour interval of this map?

25. What are the features (shown with blue contours) due E and W of Koip Peak (SW corner of map)?	
26. Use Google Earth to fly down to the top of Wilson Butte (SE corner of map). Describe its topography: (if you were standing there, what would you see)?	
 	27. The map to the left is a blowup of a portion of the Mono Craters Quad. If the highest point in this picture (x) is 8044 ft, the contour interval is 80 feet, what is the elevation of the deepest spot? *(TIP: If you encounter difficulties with this question, draw a cross-section across it!)* NOTE: 8044 is the highest point and is marked with an X. The highest point is NOT under the number 8044.


A
B
HARVARD
Glacier
Lowell
Glacier
KE
A
5500
2500
2000
1500
1000
3000
4000
4140
Anchorage (B-2), AK
0
1
2
3 kilometers
0
½
1
2 miles
Contour interval = 100 ft.
Image based on USGS map
North


Siffleur River, Alberta
North
0
1
2 kilometers
0
½
1
2 miles
Contour interval = 100 ft.
Image based on USGS map
X
Y
Siffleur
8700
8000
6000
7200
7500
9100
6500
IMPROVEMENT DISTRICT 10
IMPROVEMENT DISTRICT 9


Glacial Valley -- Anchorage
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Elevation in feet
Horizontal Axis: ~2 inches=1 mile = 5,280 ft


Stream Valley -- Alberta
11000
10500
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
Elevation in feet
Horizontal Axis: ~2 inches=1 mile = 5,280 ft

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Read a topographic map and interpret what it looks like in 3D (including identifying steep vs. gentle hills, plains, mountain tops, depressions, valleys, saddles, and ridges).	A | B | C | D | F	
Determine the elevation range of any point on a topographic map.	A | B | C | D | F	
Generate a topographic profile between any two points on a topographic map (showing elevation relief between those spots).	A | B | C | D | F	
Calculate the vertical exaggeration for any topographic profile.	A | B | C | D | F	
Use Google Earth to find elevation and topographic profiles for landforms.	A | B | C | D | F	

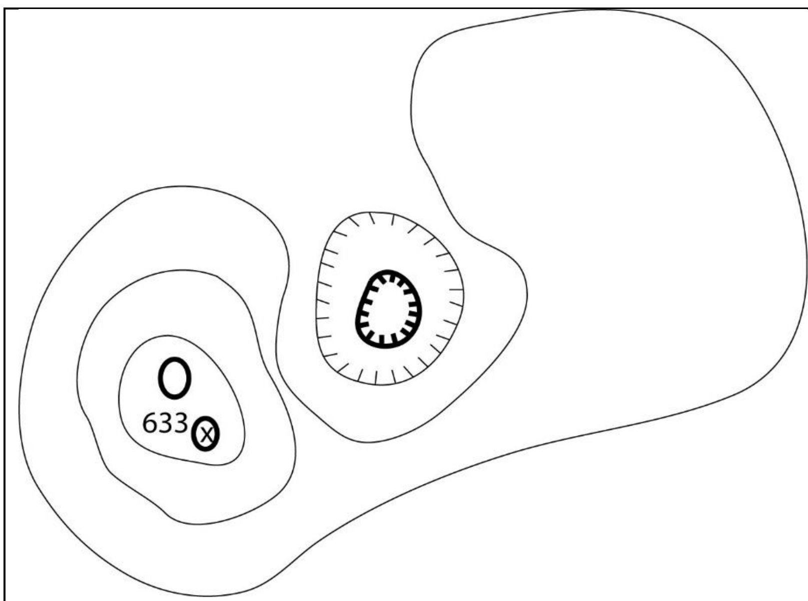
INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

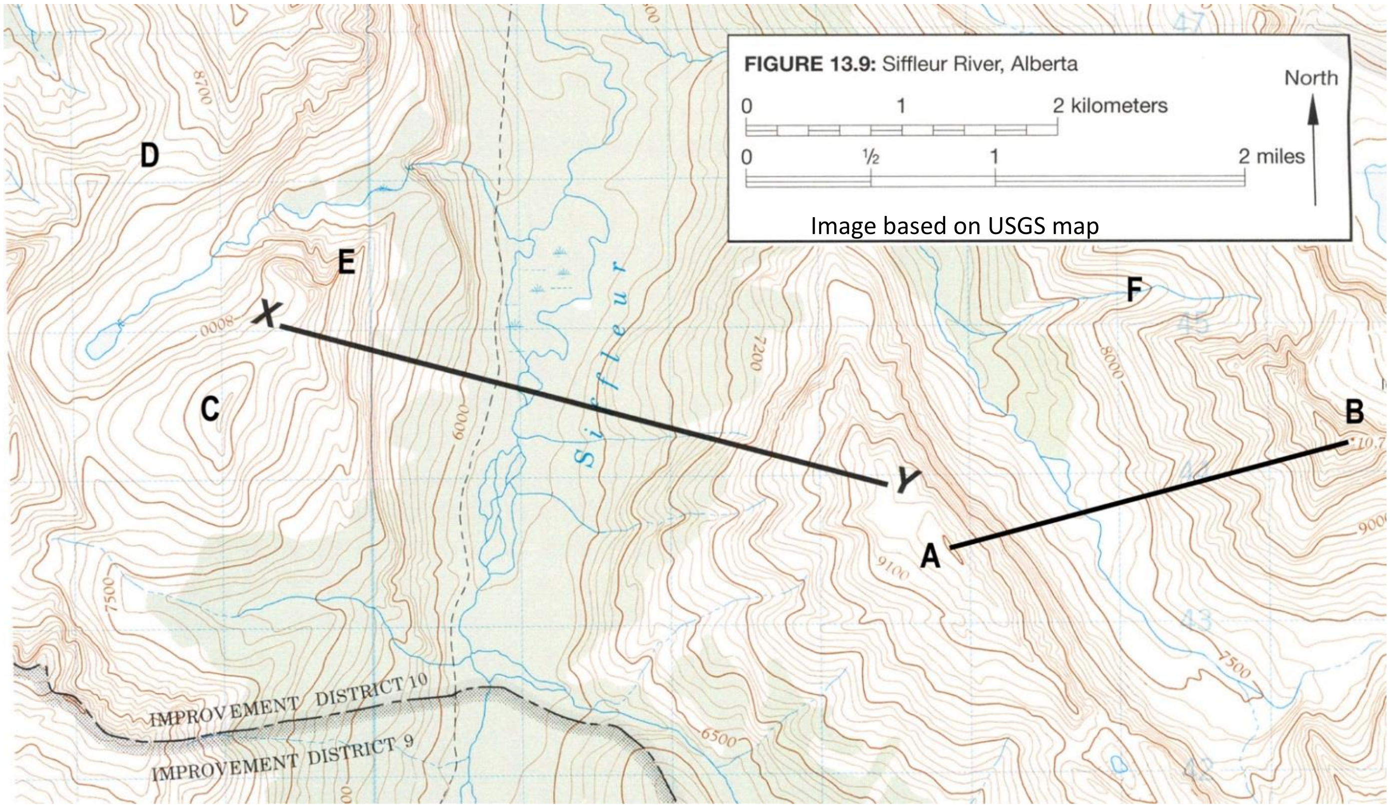
Topographic Maps Practice Sheet

Remember – the exam questions come directly from the labs, so to do well on the exam, be sure to study ALL the questions on the labs and be able to correctly answer them on the exam. To assist, this study sheet gives you a chance to practice SOME of the skills from the first labs. BE CAREFUL – just because a question appears on this sheet doesn't mean it will show up on the exam. AND if it doesn't show up here, that doesn't mean that it WILL show up on the exam. Just like on the exam, **show ALL work.** (You may use a calculator.)

1. In this space, sketch contours (at least four) to show the shape of a generic river moving downstream from north to south. Add north arrow to your drawing.	
2. In this space, sketch contours (at least 10) to show the shape of two hills with a saddle between them. **Add north arrow to your drawing.** Label the highest contour 3000 ft. Make the contour interval 100 ft. Darken index contours for every 400 ft. Add horizontal scale bar.	
3. Draw a topographic cross-section through the saddle and peaks.	
4. What is the vertical exaggeration? Show work	
5. What is the orientation of your profile line?	

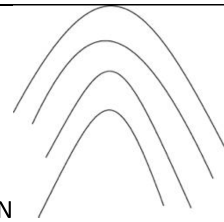
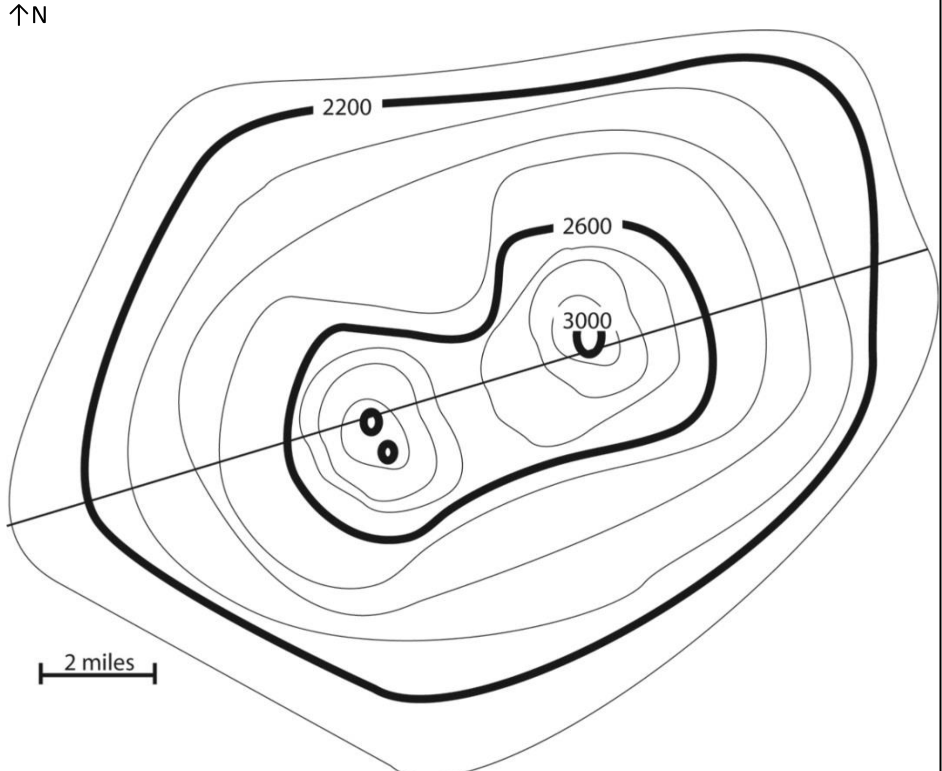
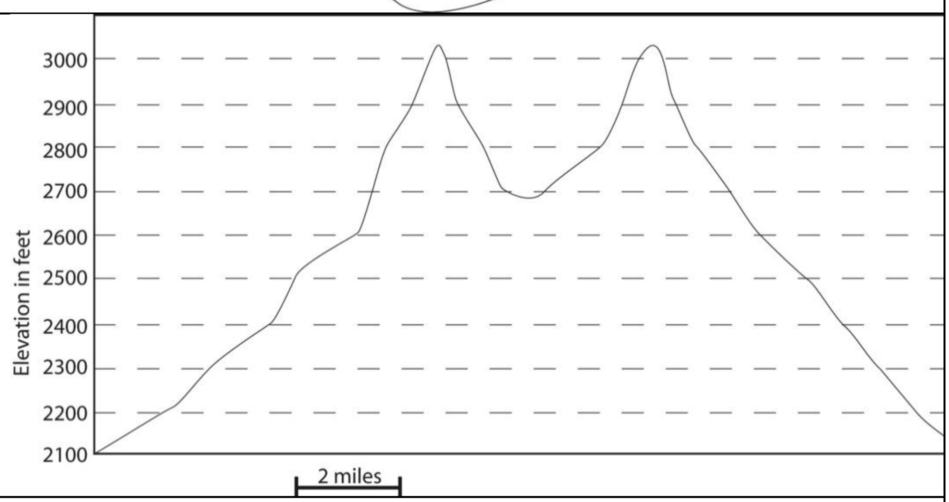


6. If the highest point in this picture is 633 ft, the contour interval is 40 ft, what is the elevation of the deepest spot?



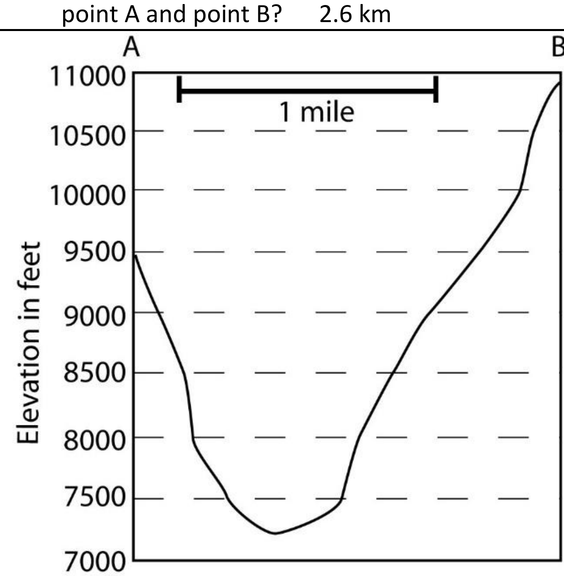
7. What is the contour interval of this map? (Don't forget units!)	8. What is the elevation of the top of the peak near point C? (Don't forget units!)
9. What is the topographic feature under point D?	10. What is the topographic feature under point E?
11. What is the topographic feature under point F?	12. What is the distance (in km) between point A and point B?
13. Complete a topographic profile across line A-B.	
14. What is the orientation of your profile line?	
15. What is the vertical exaggeration of your profile? (Show work.)	

KEY

<table>
<tr><td>1. In this space, sketch contours (at least four) to show the shape of a generic river moving downstream from north to south. Add north arrow to your drawing.</td><td>
↑N</td></tr>
<tr><td>2. In this space, sketch contours (at least 10) to show the shape of two hills with a saddle between them. <u>Add north arrow to your drawing.</u> Label the highest contour 3000 ft. Make the contour interval 100 ft. Darken index contours for every 400 ft. Add horizontal scale bar.</td><td>↑N

</td></tr>
<tr><td>3. Draw a topographic cross-section through the saddle and peaks.</td><td>
</td></tr>
<tr><td>4. What is the vertical exaggeration? Show work</td><td>2 miles = 5280ft x 2=10560 ft $\frac{\underline{10560 \text{ ft/unit}}}{233\text{ft/unit}} = 45.32$
RANGE: 10560/232.5 = 45.42 10560/233.4 = 45.24 45.3 times exaggeration</td></tr>
<tr><td>5. What is the orientation of your profile line?</td><td>N73E</td></tr>
</table>

6. If the highest point in this picture is 633 ft, the contour interval is 40 ft, what is the elevation of the deepest spot?

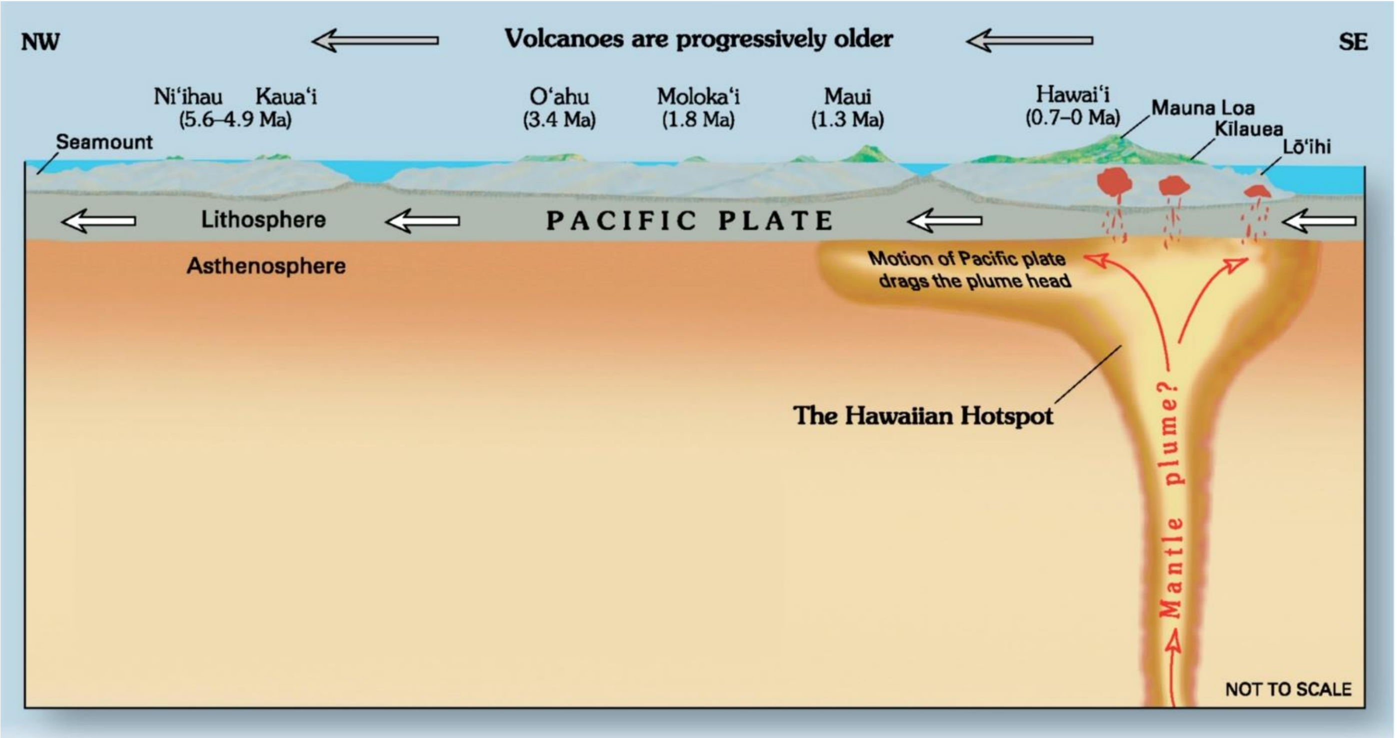
- 633 ft is highest point, then highest contour, which is an index contour is 600 ft.
- Next down is 560 ft
- Next down is 520 ft
- Next down is 480 ft
- Next down is 440 ft
- Next down (also index contour) is 400 ft
- Deepest point: 360 ft < X < 400 ft

7. What is the contour interval of this map? (Don't forget units!) 100 ft	8. What is the elevation of the top of the peak near point C? (Don't forget units!) 8700 < X < 8800 ft
9. What is the topographic feature under point D? SADDLE	10. What is the topographic feature under point E? RIDGE
11. What is the topographic feature under point F? STREAM VALLEY	12. What is the distance (in km) between point A and point B? 2.6 km
13. Complete a topographic profile across line A-B.	
14. What is the orientation of your profile line? N79E	
15. What is the vertical exaggeration of your profile? (Show work.) 1 mile = 5280 ft <u>5280 ft/3.5cm</u> = 2.4 **x** **(2.4 times exaggeration)** 2200 ft/3.5cm Range: 5280/2150ft = 2.46 5280/2240 = 2.36	

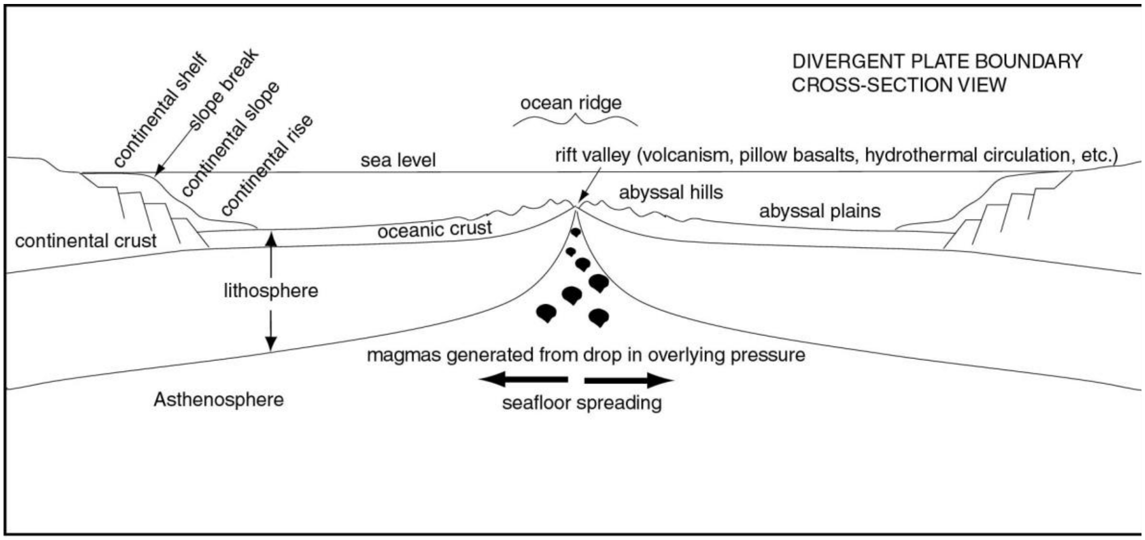
World Maps & Plate Tectonics

NEEDED SUPPLIES:

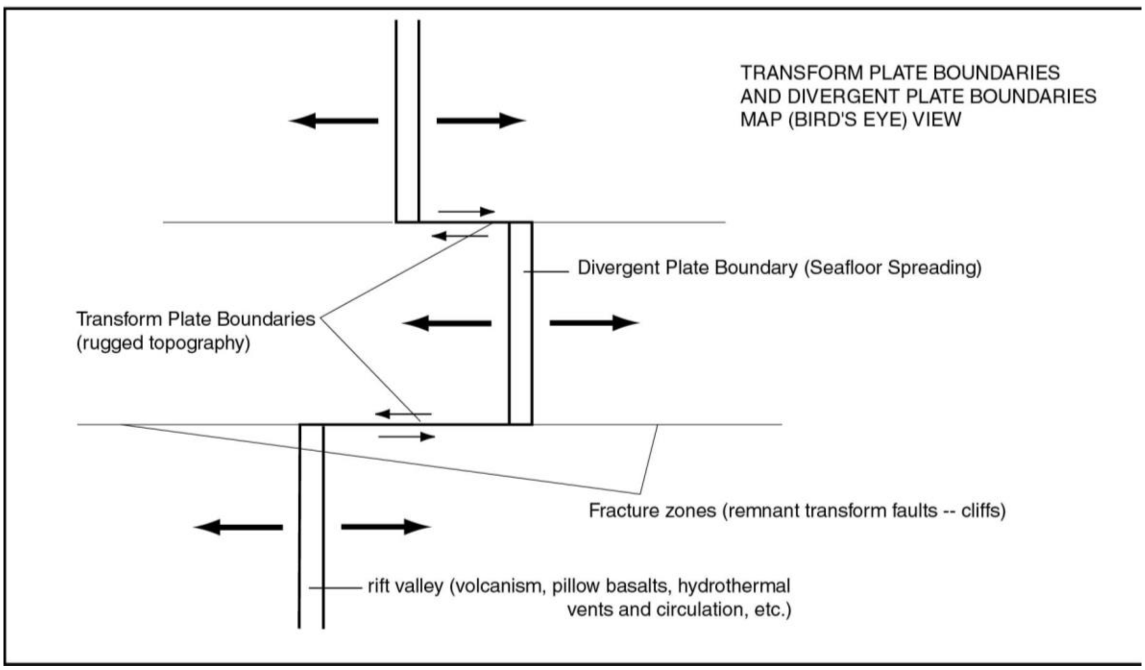
- Desktop version of Google Earth (download if you haven't already)
- Protractor to measure angles



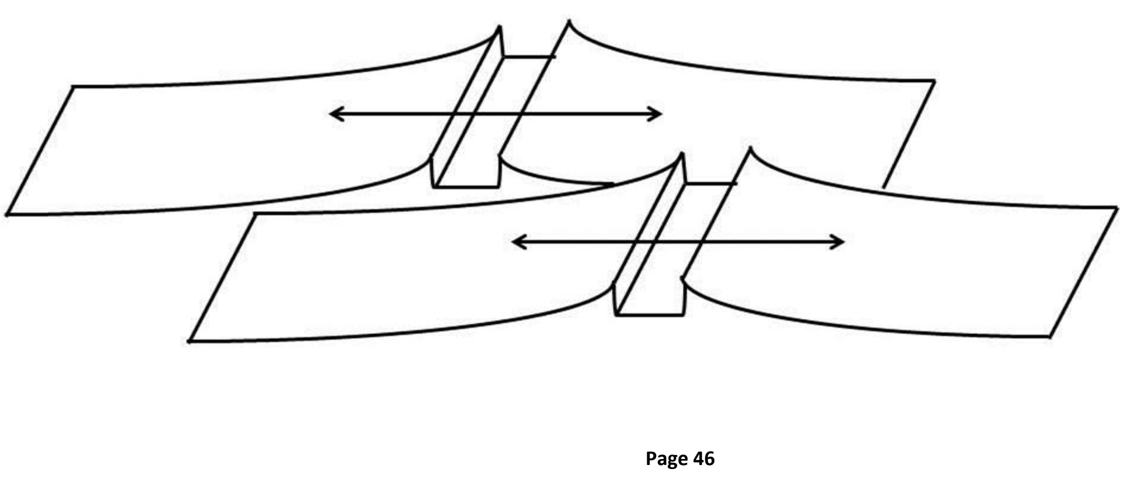
Hawaiian Hotspot Image: USGS



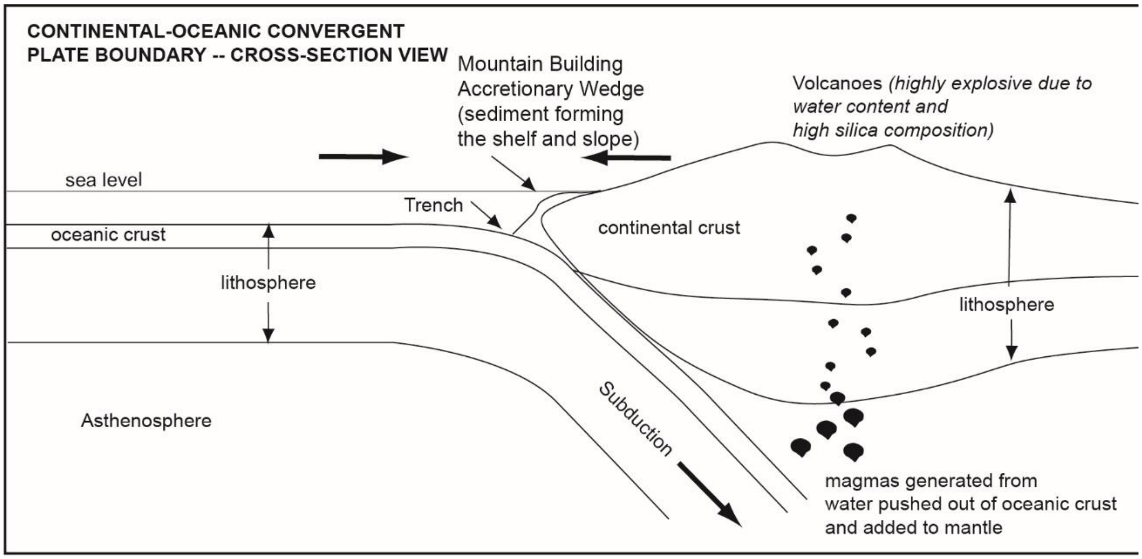
DIVERGENT MOTION: Apart
FEATURES:
Oceanic ridges. Seafloor spreading. Melted mantle rock due to reduced overlying pressure. Rift valleys with volcanism, pillow basalts, hydrothermal vents, and hydrothermal circulation. Serpentinites form at depth in mantle rocks that are undergoing hydrothermal alteration. Transform faults (associated with transform plate boundaries) break up divergent boundaries into small sections offset from one another.
WORLD EXAMPLES:
Mid-Atlantic Ridge, Iceland.

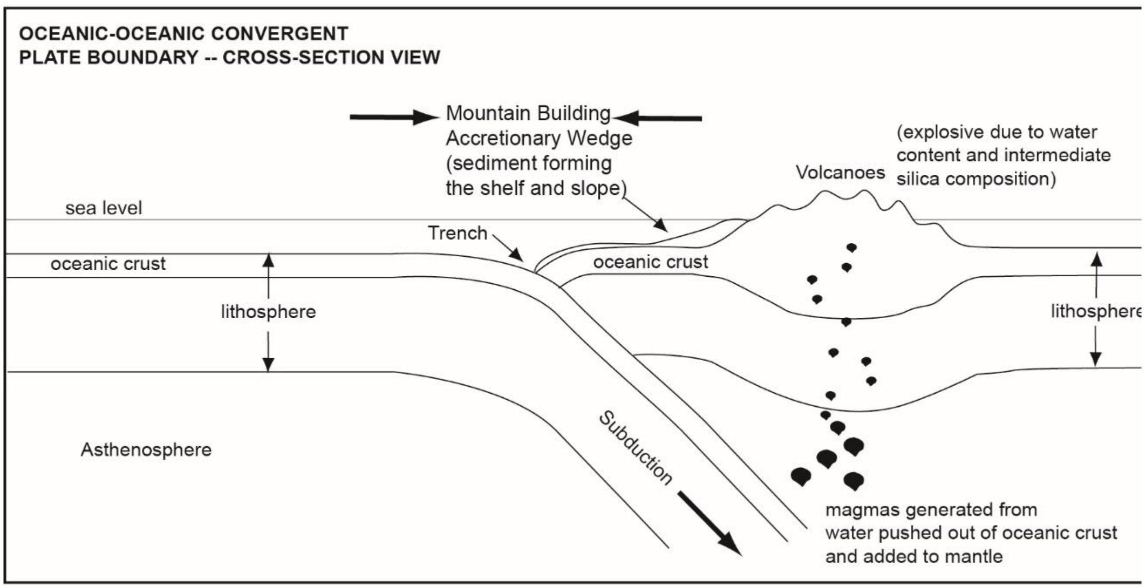


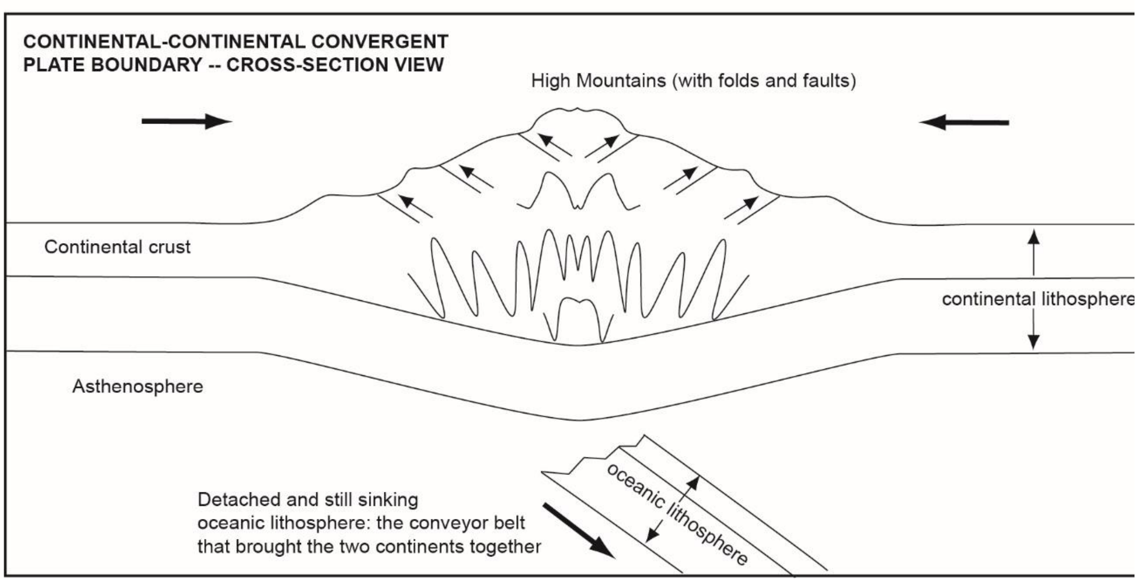
TRANSFORM MOTION: side by side
FEATURES:
Fracture zones (old transform faults, no longer active, because lithosphere on both sides are part of the same plate). Rough topography (cliffs where ridges offset. Oceanic ridges and spreading centers on both sides.
WORLD EXAMPLES:
California, Iceland



Oblique view of seafloor spreading centers and transform boundaries.







CONVERGENT MOTION:
Towards each other
FEATURES:

Continent-Ocean
Subduction zones (ocean crust sinks back into mantle). Melted mantle rock due to addition of water, which drops the melting point of the underlying mantle. Volcanoes above subduction zone. Trenches on ocean floor where ocean crust begins subducting. Accretionary wedge mountains (made up of terranes: sediments, islands, crustal blocks)
WORLD EXAMPLES:
W. coast S. America
Pacific Northwest

Ocean-Ocean
Subduction zones (ocean crust sinks back into mantle). Melted mantle rock due to addition of water, which drops the melting point of the underlying mantle. Volcanoes above subduction zone. Trenches on ocean floor where ocean crust begins subducting. Accretionary wedge mountains (made up of terranes: sediments, islands, crustal blocks)
WORLD EXAMPLES:
Japan, Philippines,
Aleutian Islands

Continent-Continent
Fold and thrust mountains, thickened lithosphere.
WORLD EXAMPLES:
Himalayas (India)
Alps (Europe)

World Maps & Plate Tectonics – Prereading Exercises

Read *Plate Tectonics* chapters in lecture textbook and answer the attached questions. (Okay to read other text, if good.)

Speed Like highway speed, 70 miles/hr, speed = distance ÷ time. Speed (S) = $\frac{\text{Distance (D)}}{\text{Time (T)}}$

Solved, algebraically, for distance and time, you get three total equations:

$S = \frac{D}{T}$	To solve for DISTANCE (D), multiply both sides by T	$T \times S = \frac{D}{\not{T}} \times \not{T}$	D = SxT	To solve for TIME (T), divide both sides by S	$\frac{D}{S} = \frac{\not{S} \times T}{\not{S}}$	$T = \frac{D}{S}$

A. If it takes 3.2 hours to arrive at a party, and you travel at 43 miles per hour, how far do you travel?

D = SxT $D = \frac{43 \text{ mi}}{\text{hr}} \times 3.2\ \not{\text{hr}}$ D = 137.6 miles D = 140miles

End members for precision are 43.4 miles and 42.5 miles and 3.15 hours and 3.24 hours. End member distances: 3.24 hr x 43.4 miles/hr = 140.6 miles; 3.15 hr x 42.5 miles/hr = 133.9 miles; the hundreds place is the same for all; the first place (from left) to change is the tens place, so round original answer to tens place.

B. If you travel 6 miles by bicycle at an average of 11 miles per hour, how long does it take you arrive?

$T = \frac{D}{S}$ $T = \frac{6 \text{ mi}}{11 \text{ mi/hr}}$ $T = 6\ \not{\text{mi}} \times \frac{1 \text{ hr}}{11\ \not{\text{mi}}}$ T = 0.5455 hr T = 0.5 hr

End members for precision are 6.4 miles and 5.5 miles and 11.4 mph and 10.5 mph. End member times: 6.4 mi ÷10. 5 miles/hr = 0.61 hr; 5.5 mi ÷ 11.4 miles/hr = 0.48 hr; there are no places the same for all; the first place that changes is one decimal place, so round to one decimal place.

C. If you walked 3 miles, and it took you 1.4 hours to do so, how fast did you walk?

$S = \frac{D}{T}$ $S = \frac{3 \text{ mi}}{1.4 \text{ hr}}$ $S = 2.143 \frac{\text{mi}}{\text{hr}}$ $S = 2 \frac{\text{mi}}{\textbf{hr}}$

End members for precision are 3.4 mi and 2.5 mi and 1.44 hr and 1.35 hr. Thus, end member distances: 3.4 mi ÷1.35 hr = 2.5 mph; 2.5 mi ÷ 1.44 hr = 1.7 mph; there are no places the same for all; the first place that changes is the ones place, so round original answer to the ones place.

Remember to round for correct precision in answer. ***Show ALL work – all steps – with units throughout!***

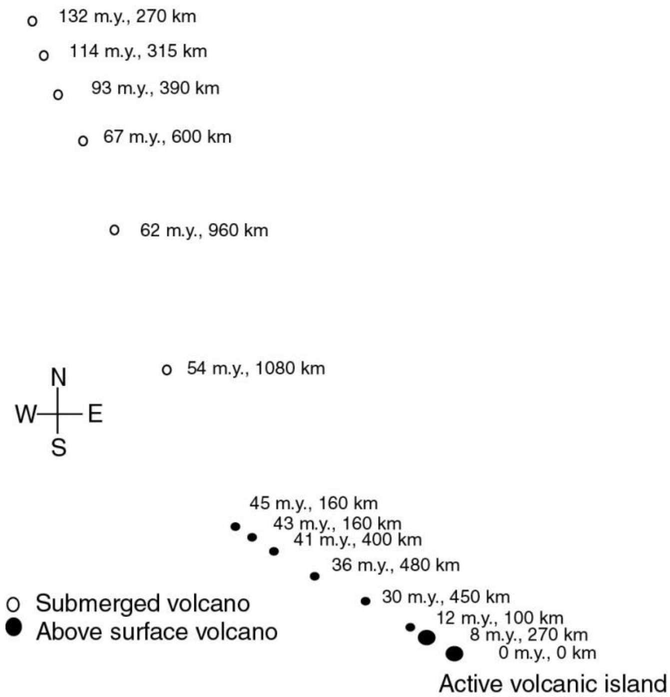
1. If a tsunami travels through the water from point A to point B (1602 km apart) in 2.1 hrs, how fast was it moving in km/hr? (Ranges: 1602.4 km, 1601.5 km; 2.14 hr, 2.05 hr)

2. If a lava flow travels at a speed of 4.5 km/hr. How far can it travel in 3.3 hours? (Ranges: 4.54-4.45 km/hr; 3.34-3.25 hr)

3. Convert 32.6 cm/yr to km/my. (It could be as big as 32.64 cm/yr or as low as 32.55 cm/yr.) **Note:** treat these unit the same as if they weren't already fractions. cm/yr *(centimeters per year)* is a single unit, like a dollar. km/my *(kilometers per million years)* is a single unit, like a penny. Conversion factor: 10 km/my = 1 cm/yr.

4. If an ocean plate travels at a speed of 11 cm/yr. How long would it take it to travel 6 km? (Ranges: 11.4 to 10.5 cm/yr; 6.4-5.5 km))

Hawaiian-Emperor Seamount Chain



5. Numbers to the right of each volcanic landform indicate age of each island in millions of years (m.y.) and distance away from next youngest landform. *Example: the third volcano from the bottom right corner is 12 million years old and 100 km away from the center of the 8 million-year-old volcano.* If you are using a hotspot track to determine the speed that a plate has been moving over the hotspot, measure the distance between islands and then determine the amount of time it took the plate to move that distance. For this exercise, calculate the average speed the plate traveled BETWEEN each island.

Remember: $1 \frac{cm}{yr} = 10 \frac{km}{my}$

Age range (m.y.)	Distance between islands (km)	Average rate of plate motion during interval (km/m.y.) ***Round answers to ones place.***	Average rate of plate motion during interval (cm/year) ***Round answers to one decimal place.***
0-8	270		
8-12	100		
12-30	450		
30-36	480	$\frac{480 \text{ km}}{6 \text{ my}} = \frac{80 \text{ km}}{\text{my}}$	$8.0 \frac{\text{cm}}{\text{yr}}$
36-41	400		
41-43	160		
43-45	160		
45-54	1080		
54-62	960		
62-67	600		
67-93	390		
93-114	315		
114-132	270		

World Maps & Plate Tectonics – Lab Exercises

*** THROUGHOUT THIS LAB, SHOW ALL WORK

1. The Hawaiian chain and Emperor Seamount chain are a continuous chain of one hotspot's activity. The distribution of volcanoes indicates two different plate directions. **Draw two arrows on Prereading Figure** to indicate these two directions of plate motion. Measure the angles with a protractor and describe their orientations below. Determine the most likely time when plate motion changed and enter into spaces below.

Recent plate motion direction	Time (m.y.)	Oldest plate motion direction	Time (m.y.)
	0 Ma to		to 132 Ma

2. Check your answers to the above by going onto Google Earth & Oceans and measuring the headings (using the Ruler tool). Do you get the same answers? Why or why not?

3. Based on the information in the preceding tables, specifically describe **when** and **how speed** and **direction** of Pacific Plate motion changed. Don't explain why! Just describe the changes (be a narrator or storyteller). Describe all speed and direction changes – value and time of change. Remember, stories begin in the past and move forward to today.

4. Loihi is the name of the currently growing "new" hotspot volcanism. Locate it in Google Earth & Oceans and give the latitude and longitude.

Mono Craters

5.	Use Google Earth desktop version to draw a Path (ruler tool > Path tab) FROM San Francisco TO Mono Lake. Check box for Show Elevation Profile and describe it below:
6.	Use Google Earth to locate Panum Crater, just south of Mono Lake. Click 3D to see what it looks like in 3D. What kind of structure does it look like? Shape?
7.	Compare the above description with the same location visible in the Mono Craters Topographic map (might be called North Crater, depending on the particular date map you view). What is the highest elevation shown on that map for that mountain? What are the hachured marks indicating?

World Maps (Use physical globes, Google Earth & Oceans, and maps of the world)

8.	The British Isles are perched atop the continental shelf of Europe. Continental shelves are the true edges of the continents: sea level during ice ages. Describe **<u>two</u>** other locations where land bridges would have existed between modern-day islands during the last ice age.
9.	Find the Azores islands. Find Bermuda. At which of these locations would you find older rocks? Why?
10.	Find Iceland. Why did an island form over the Mid-Atlantic Ridge where Iceland is today? (Think about what is required to produce so much excess volcanism.What are the sources of the volcanism?)
11.	The Marianas Trench is the location of the deepest point on Earth – approximately 11,000 meters (11 km). Give the latitude and longitude of the center of this trench.
12.	The Bay of Bengal and the Arabian Basin are smooth abyssal plains. Abyssal plains are so smooth in general because of loads of sediment that settle and collect on them over time, covering any rough topography. Why in this place specifically? (Look at the continental features nearby.)

13. Use Google Earth & Oceans to locate the following: 43°41'26.51"N & 128°37'24.21"W. What type of plate boundary is located at this point? What's the evidence?

14. On the map below, label plate boundaries. I recommend that to make these visible, you use a sharpie, or find a piece of flat transparent plastic (like a page protector) – cut a piece and tape it over this image, then write your boundaries with a marker.

Google © 2013 NASA, TerraMetrics, Map data © 2014 Google, INEGI

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Use hotspot track and magnetic anomaly data to calculate the direction and speed of plate motion.	A | B | C | D | F	
Use plate motion speed to estimate the opening date of ocean basins.	A | B | C | D | F	
Compare and contrast the landforms and features associated with various plate boundaries and plate tectonics processes and identify these on world maps.	A | B | C | D | F	
Use Google Earth to explore landforms across the planet and see them in 3D.	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Structural Geology

NEEDED SUPPLIES:

- Protractor, Ruler (and drafting triangles if you have them – optional)
- Scissors
- Pencil and eraser (***colored pencils: optiona***l)

Relative dating of rock layers

Geologists piece together Earth history from the geologic record of past events. Events include intrusions and extrusions of igneous rock, crustal metamorphism and deformation accompanying mountain building, and the erosion and deposition of sediments. Information about Earth's geologic history comes largely from exposures of rocks and sediment at the surface called **outcrops**. To understand history, we need to view it in **cross section**, like viewing a slice of it edge on. Outcrops at highway excavations, railroad cuts, stream valleys, and cliffs all provide a cross section of Earth's crust.

Cross sections of sedimentary rocks reveal layers called **strata**. The study of strata is **stratigraphy**. Building the geologic time scale has required modern science to develop techniques to determine the age of rocks, minerals, and sediments. **Relative dating** involves interpreting the sequential relations between different rocks and the events they record. **Radiometric dating** involves calculating the numerical age of certain Earth materials and makes use of the natural phenomenon of radioactivity.

Relative dating is a technique of dating a rock unit relative to other nearby strata. The relative ages of two strata can be fixed in terms of which came first and which second. Those two strata then can be dated relative to a third stratum, and so on. This process continues until all the layers in a cross section are ordered within a relative time scale that reflects a sequence of events. The relative ages of many strata in a complex portion of crust can be established through the use of various principles:

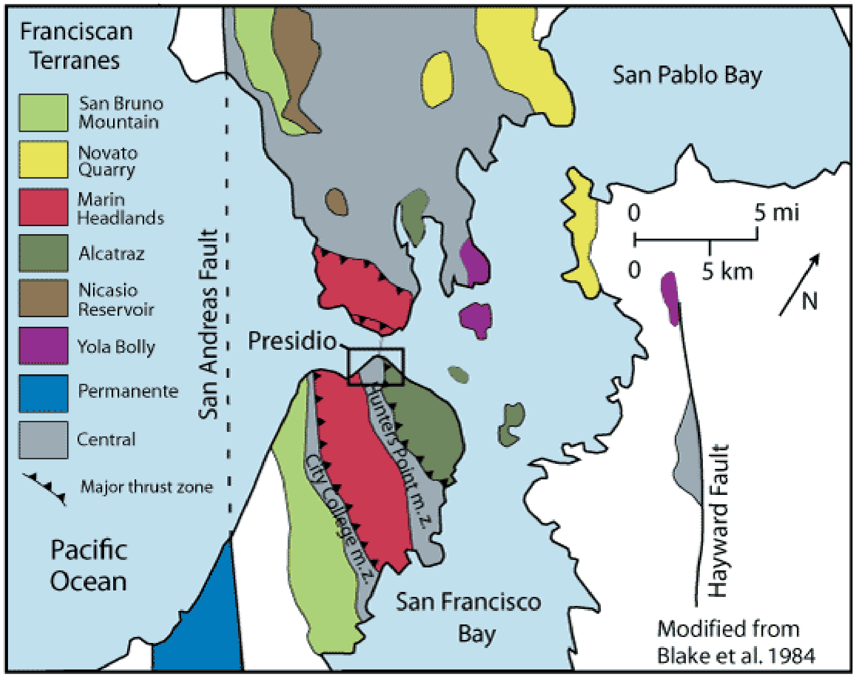
- **The Principle of Original Horizontality** describes the tendency for sediments to be deposited in horizontal beds. If left undisturbed, particles of sediment accumulate in beds that are parallel to this surface. Tilted or folded sedimentary strata record tectonic events that have deformed Earth's crust.
- **Principle of Original Lateral Continuity** describes the tendency for lava flows and sedimentary beds to extend laterally in all directions until they thin to nothing or reach the edge of the deposition basin.
- **The Principle of Superposition** states that the lowest sedimentary rocks in an undisturbed sequence were deposited first and therefore are oldest. Vertical sequences of different rock types are often exposed in cliff faces. If such a sequence is undeformed, the lowest layer of rock is the oldest, and the highest is the youngest. The intervening strata represent a sequence of successive ages between the two extremes.
- **The Principle of Cross-Cutting Relations** describes how certain geologic events (such as folding, faulting, intrusion, and erosion) are younger than the rock bodies they alter. For example, igneous intrusions are younger than the surrounding crustal rock they intrude, and faults are younger than the strata they fracture. It is often possible to determine the relative ages of several mutually cross-cutting intrusions and faults.

Structural views of the Earth's crust

Geologists interpret underground geology by studying outcrops above ground. First geologists map surface rocks. In this way, they get an accurate record of where each bed appears and how thick its surface exposure is. For each outcrop, geologists measure the bed's orientation or attitude (strike and dip), so they can project how that bed will continue underground.

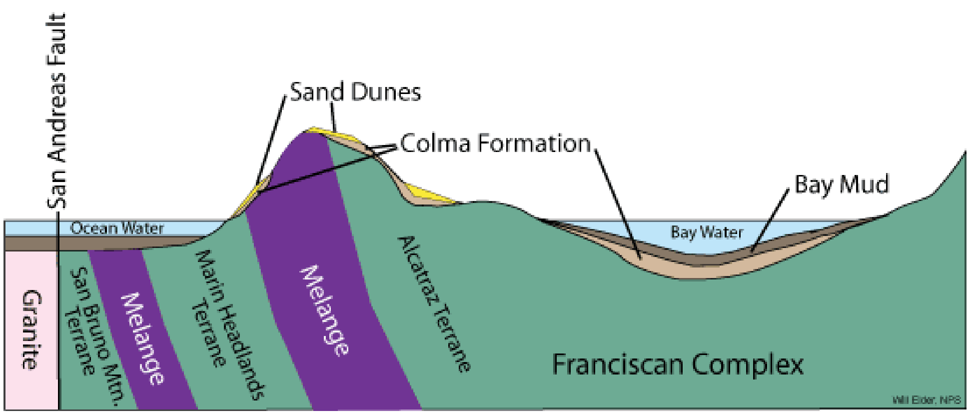
- **Map View** - a two-dimensional representation of Earth's surface as viewed from above, such as a street map, topographic map, or a geologic map.
- **Geologic map** – a map view showing the distribution of rocks at Earth's surface. Rocks are commonly divided into mappable units (*formations*). The boundaries between formations are contacts, which form lines on geologic maps. A geologic map is both a geologic and topographic map. The geologic map below, shows the major geologic units of the San Francisco Peninsula.
- **Geologic cross section** – a cutaway view of Earth. It shows the arrangement of formations and their contacts as they extend underground. A good cross section is also a topographic profile. The middle image is cross section across the San Francisco Peninsula from east to west (looking north)
- **Block diagram** – a three-dimensional view of the crust and is a combination of the geologic map and four cross sections. It is meant to represent a solid block of a portion of Earth's crust. They show the surface rock outcrops (which you can walk on in the field), and detail exactly how those rocks continue under the surface. The lower image is a block diagram of the San Francisco

Peninsula. When you can see the geology of an area in three dimensions, you can do better city planning, reduce property risks and hazards, and better search for water, gold, or oil. But how do we know what's going on under the surface?

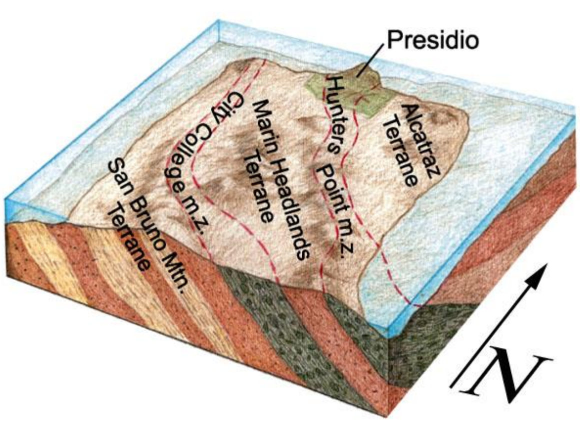


Generalized
GEOLOGIC MAP of San Francisco
Image: Will Elder, National Park Service

***Notes: The grey "Central" rock unit is found mostly north in Marin and east along the Hayward fault. The grey zones seen in San Francisco are mélange zones (not labeled in the rock unit list on left (the stratigraphy), which is the order of events from youngest at top to oldest at bottom.*



Generalized
GEOLOGIC
CROSS-SECTION:
from west to east (looking north) across the northern edge of San Francisco.
Image: Will Elder, National Park Service



BLOCK DIAGRAM: This picture shows how five tilted rock formations that underlay San Francisco are oriented in three dimensions.
Image: Will Elder, National Park Service

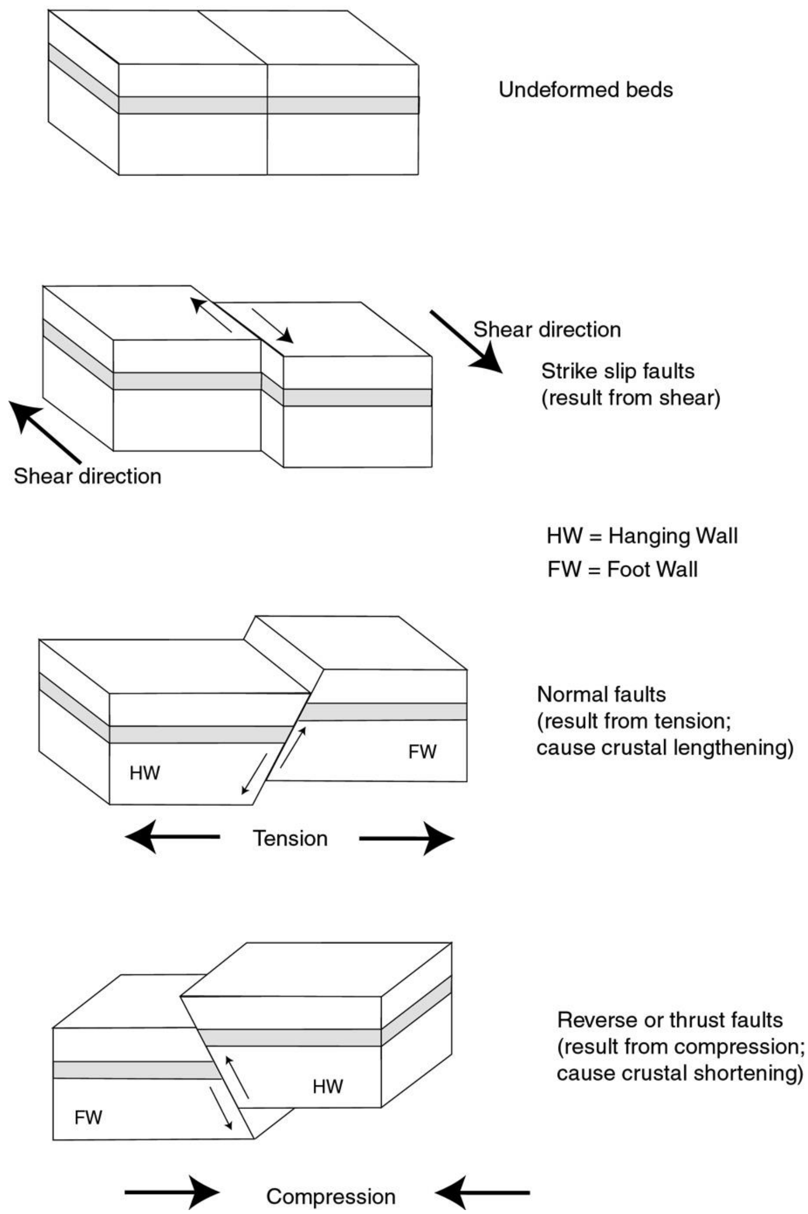
Faults

Faults are breaks in rock units along which movement has occurred. Faults form when brittle rocks undergo stress: **tension** (pulling apart or lengthening), **compression** (pushing together, compacting, and shortening), or **shear** (smearing or tearing). Faults can have horizontal slip (along strike – called **strike-slip faults**), vertical slip (along dip – called **dip-slip faults**), or a combination of the two (called oblique-slip faults).

Faults are classified by the motion of rocks on one side of the fault relative to the other. For dip-slip faults, the top surface of the fault is the **hanging wall**. (Think of this as the block of rock that is hanging over the fault surface.) The bottom surface of the fault is the **footwall**. The hanging wall rocks sit on top of the footwall rocks.

Normal faults are caused by tension (rock lengthening). As tensional stress pulls the rocks apart, gravity pulls down the hanging block. Therefore, normal faulting gets its name because it is a normal response to gravity. If the hanging wall has moved downward in relation to the footwall, then the fault is a normal fault.

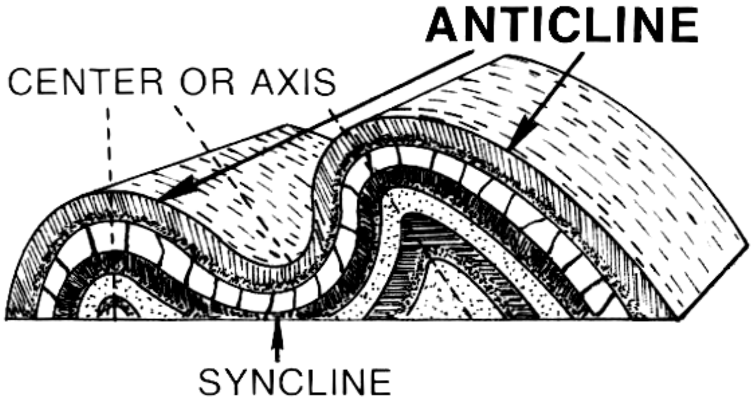
Reverse faults are caused by compression (rock shortening). As stress pushes rocks together, one rock block rides up atop another. If the hanging wall has moved upward relative to the footwall, the fault is a reverse fault. **Thrust faults** are reverse faults that develop at a very low angles and may be difficult to recognize.



Strike-slip faults are caused by shear and involve horizontal motions of rocks. Along a **right-lateral** strike-slip fault, rocks on one side of the fault appear to have slipped right relative to those on the other side. Along a **left-lateral** strike-slip fault, rocks appear to have slipped left.

Folds

Folds are bends in originally horizontal rock layers. Synclines are U-shaped. Anticlines are opposite: A-shaped. An imaginary plane, called an **axial plane**, can be drawn that bisects the fold. The **hinge line** is an imaginary line that is formed if you could take any layer in the fold and show the way it hangs or "hinges" at the axial plane (like the location of a door hinge where a door meets its frame). If the axial plane is vertical then the hinge line is a horizontal line, and the fold is upright. If the axial plane is NOT vertical, but instead tilted, we call it a tilted fold and usually give the dip angle of the axial plane. For example, in the left-most image on the next page, the left-most anticline is upright (untilted), but both the syncline and anticline have axial planes dipping eastward (if we assume that north is towards the top of the image). The angle looks to be at roughly 60°E, so we call the right-most folds a syncline and anticline with hinge axes dipping 60°E.



Left structure: Anticline with Vertical Hinge Axis.
Center structure: Syncline with titled hinge axis (dips toward east, IF the structure is aligned with North at the top).
Right structure: anticline with tilted hinge axis (same dip as syncline).
Image: Public domain.

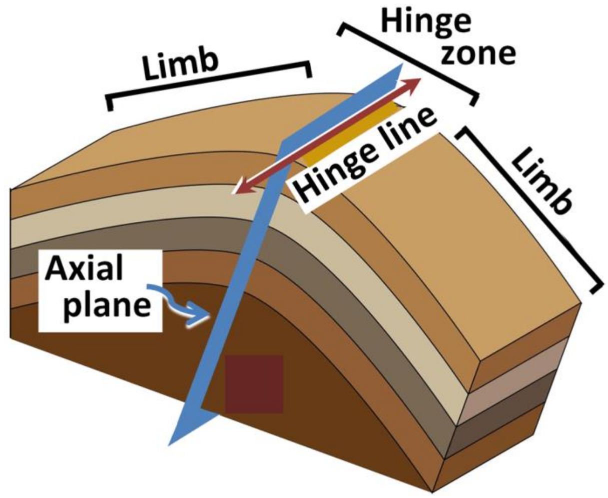
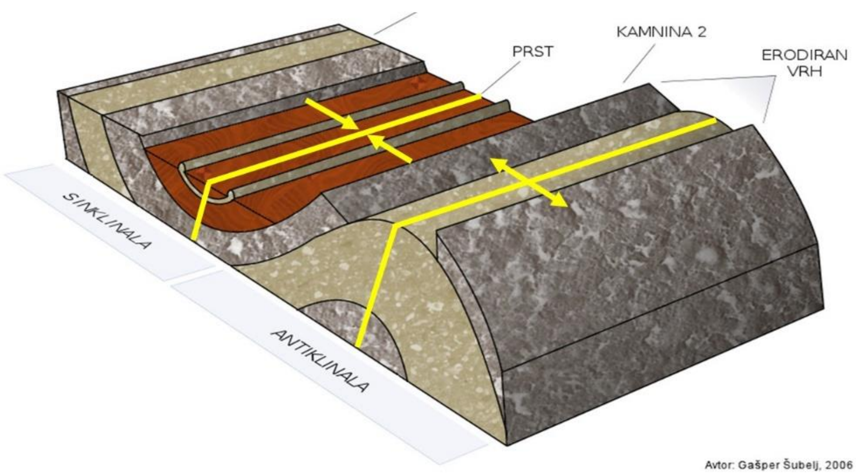
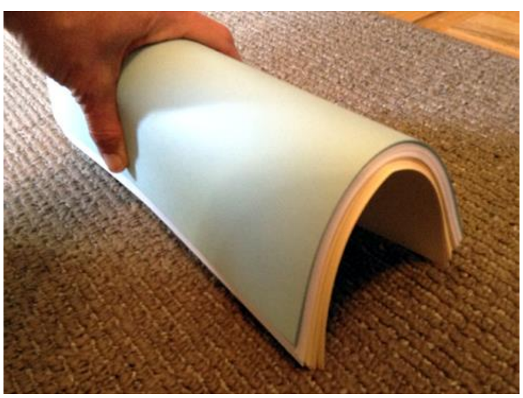


Image: Brews Ohare – Creative Commons – BY-SA 3.0



In this picture of an eroded syncline and anticline, we can see that the youngest rocks, which originally were on the top, are now visible along the inside of the eroded syncline and the edge of the eroded anticline. The oldest rocks are on the edge of the eroded syncline and the center of the eroded anticline.
Image: Modified from image by Gašper Šubelj – Creative Commons – BY-SA 3.0

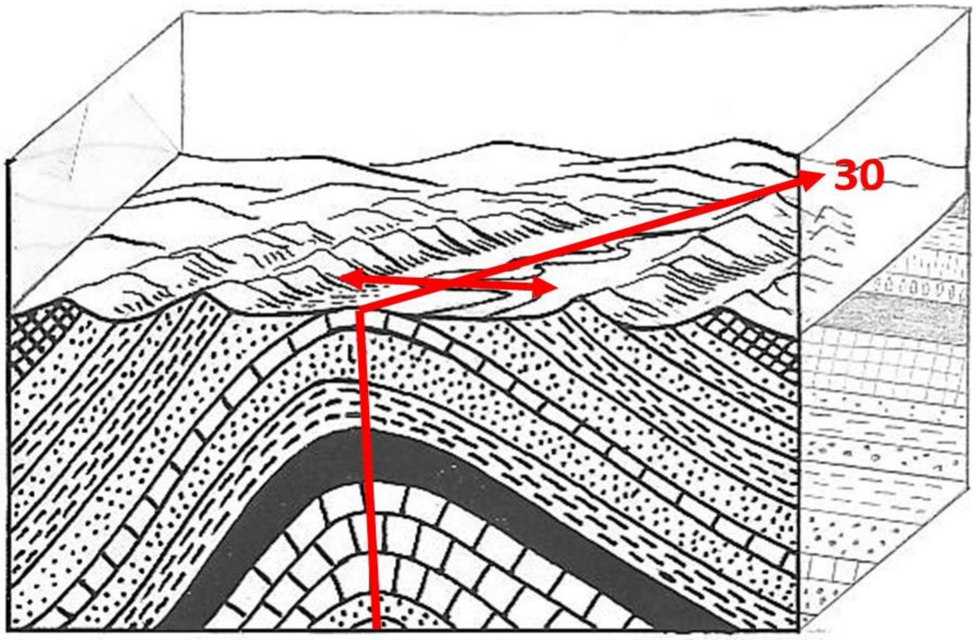
A fold can also plunge into the ground, then the axial plane might still be vertical, but the hinge line will also plunge. The fold is called a **plunging fold. Plunge** (similar to dip) is the angle between the hinge line and a horizontal line. **Trend** (similar to strike) is the orientation of the hinge line. For example, a plunging anticline with a hinge line plunge of 20°N, and a trend of due north (or N0W) would be lined up N-S, and the entire structure would plunge into the ground towards the north.



Nonplunging Anticline

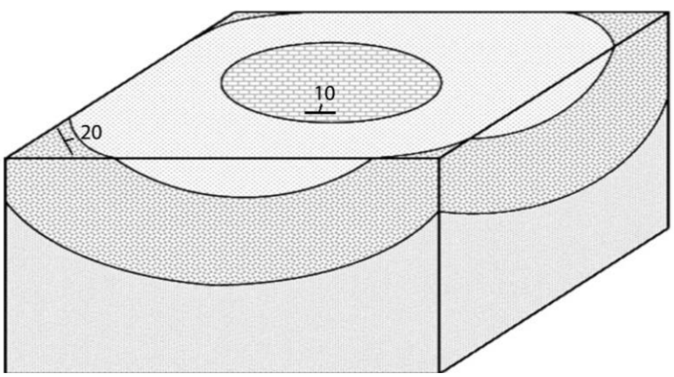
Plunging Anticline (plunge direction is to left in this image)

Plunging synclines and anticlines show horseshoe-shaped outcrop patterns on eroded surfaces. For anticlines, the horseshoe bends in the plunge direction. For synclines, the open side of the horseshoe is in the plunge direction. The oldest rocks appear in the center of anticlines and the edges of synclines.

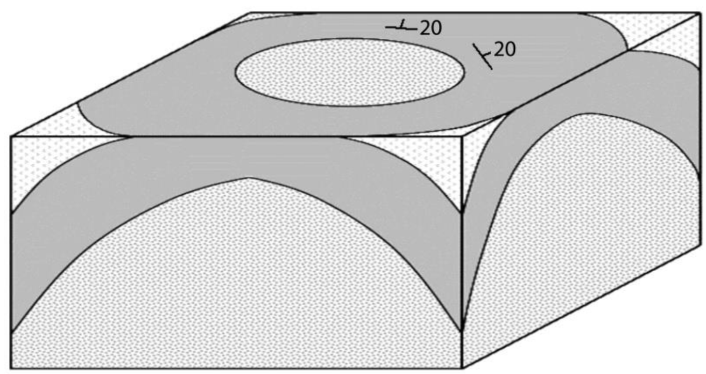


30NE Plunging Anticline (assuming North is the top of the image). Image modified from image from public domain.

Domes and basins are large, somewhat circular structures formed when strata are warped upward (domes) or downward (basins). Strata are oldest at the center of a dome, and youngest at the center of a basin.



Basin image modified from image by Ralph Dawes and Cheryl Dawes –CC BY-SA-3.0



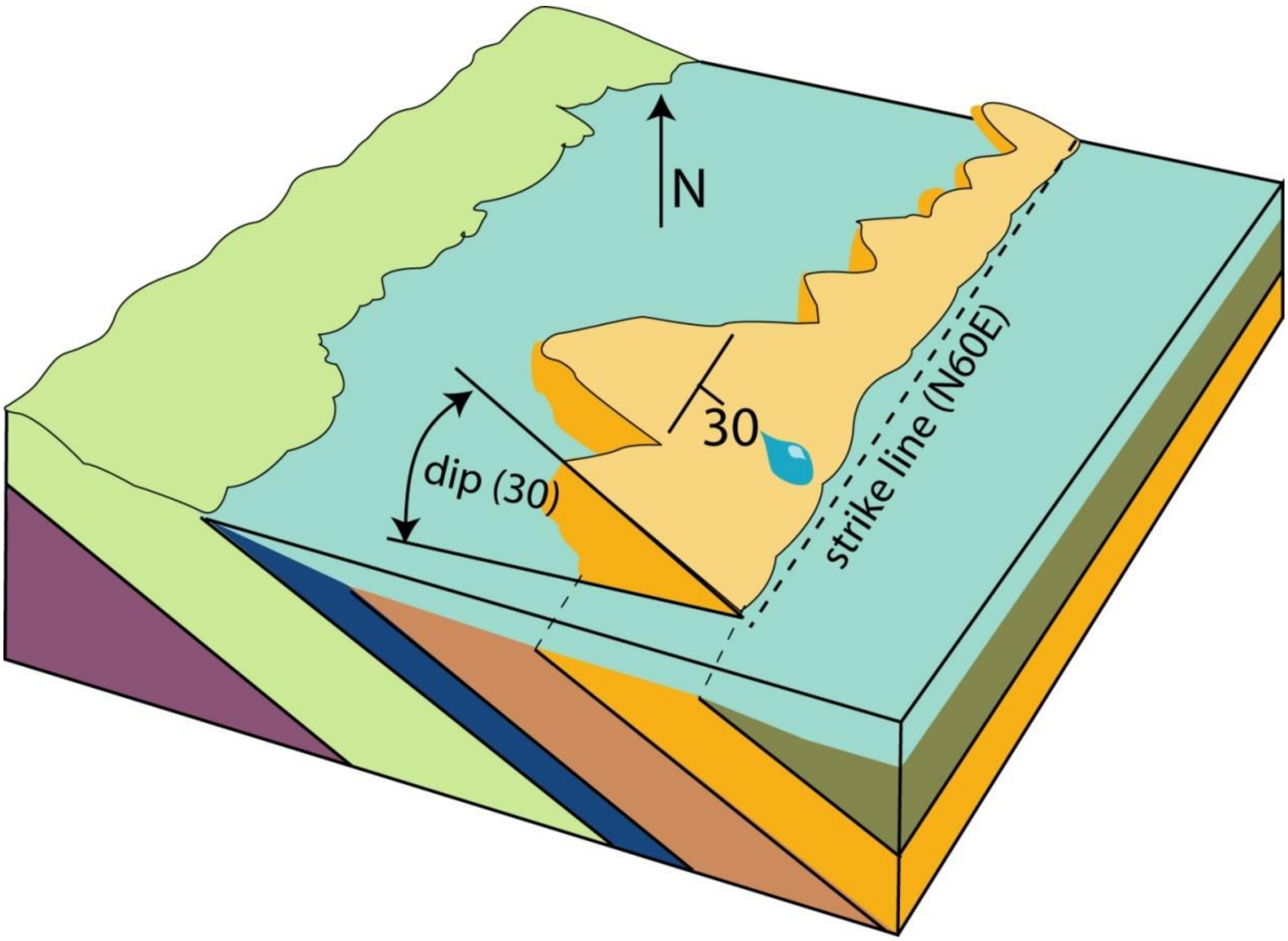
Dome image modified from image by Ralph Dawes and Cheryl Dawes – CC BY-SA-3.0

Measuring the attitude of rock units

Attitude is orientation of the surface of any mappable geologic structural feature, such as a fault or a contact between two rock layers. Attitudes consist of two components:

- **Strike** is the orientation of the line that forms when the surface being measured is intersected by a horizontal plane. You can find this line by laying a carpentry level across the bed surface. When level, the line where the surface and level meet is the strike line. Because strike is the orientation of a line, it is expressed relative to north like we have been doing in the first few labs. (NXE or NXW where $X \leq 90°$; example: N15W +/-2°.)
- **Dip** is the angle formed between a horizontal surface and the surface being measured. A thin stream of water poured onto the bedding surface always runs down the surface in the exact dip direction, which is always perpendicular to strike line. Dip is expressed as an angle and the direction water would flow. Example: 30°SW +/-2° means the bed is dipping at a 30° angle into the ground towards the southwest.

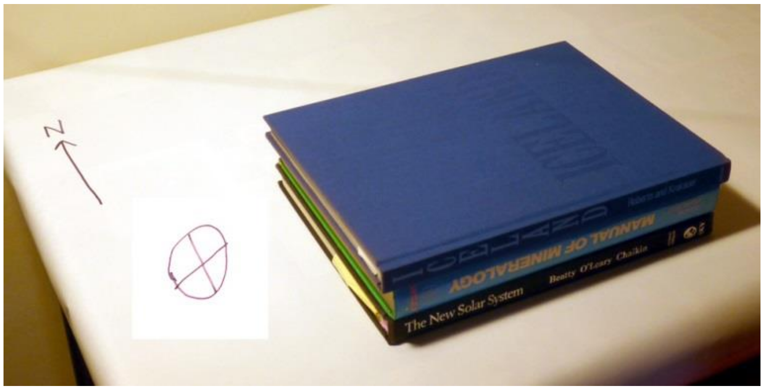
The water-on-the-rock method for finding the direction and angle of dip is very useful. Because strike is perpendicular to dip, finding one helps you find the other. Strike and dip are shown on maps with T-shaped symbols. The long line shows strike direction; the short line shows dip direction. Dip is always drawn perpendicular to the strike line. The short line points down dip. Dip angle in degrees is written under the dip line. Note: True dip angles can be seen only in cross section if the cross section is perpendicular to the fault, to the strike of the beds, or to the hinge axes of folds.



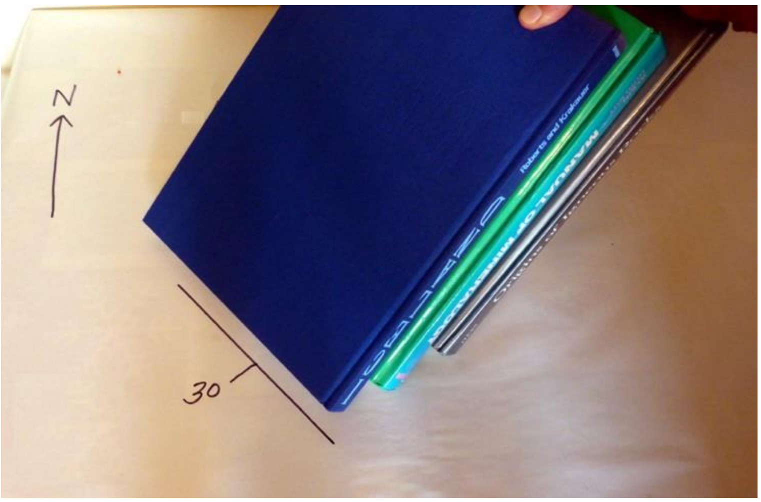
Examples:

Strike: N60W +/-2°   Dip: 75NE +/-2°

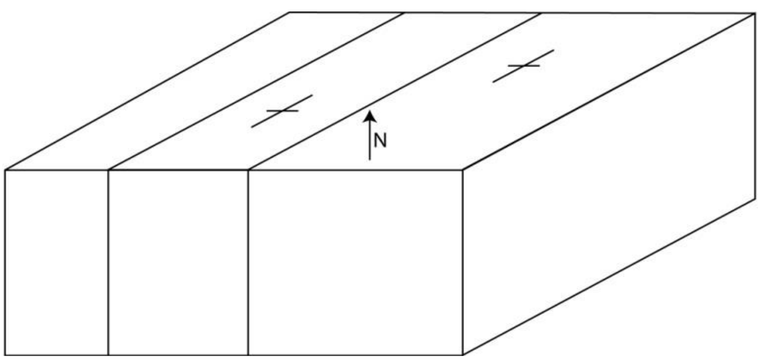
Strike: N60W +/-2°   Dip: 30NE +/-2°



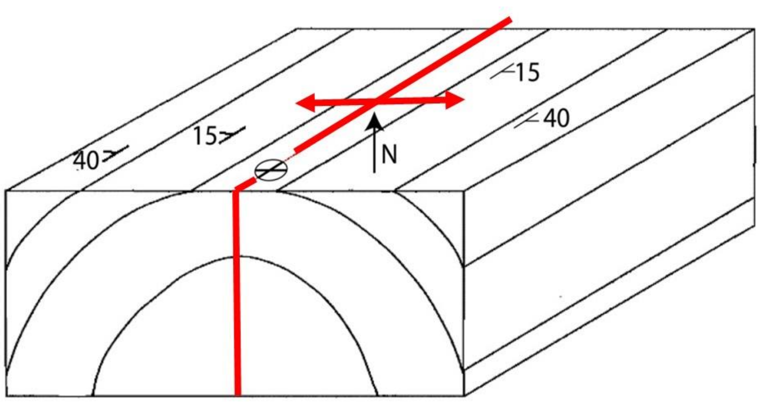
The beds above (yes, they're really books!) are horizontal. Since horizontal beds do not intersect horizontal surfaces, there is no strike line. And the dip is 0º. The symbol shown above illustrates how geologists mark such a bedding attitude on a map.



The beds above (yes, they're really books!) are striking N35W +/-2°. And the dip is 30° towards the SW The symbol shown above illustrates how geologists mark such a bedding attitude on a map.



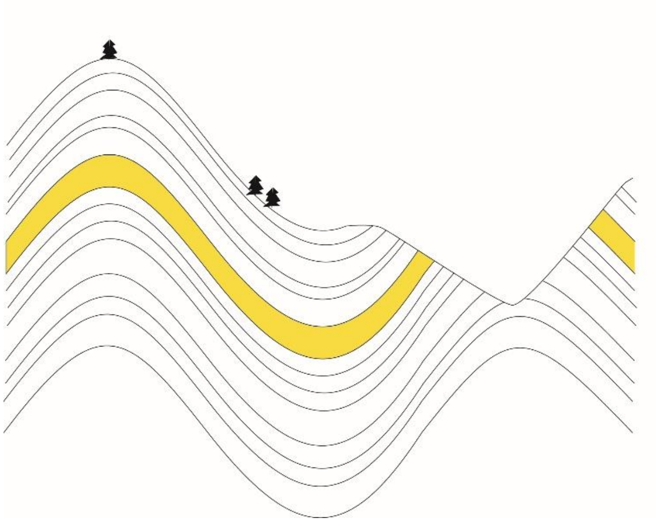
The beds to the left are vertical. The strike line in this case is approximately N30E +/-2°. And the dip is 90°. The symbol shown above illustrates how geologists mark such a bedding attitude on a map. Note that instead of marking the dip number on the surface, there are two dip ticks on both sides of the strike line.

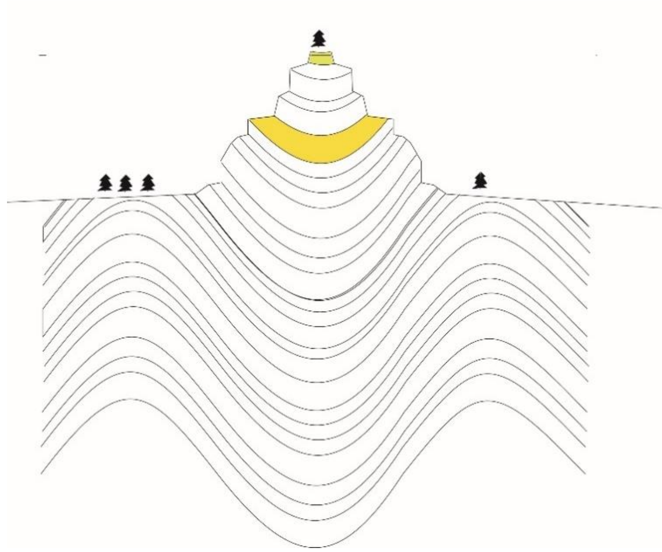


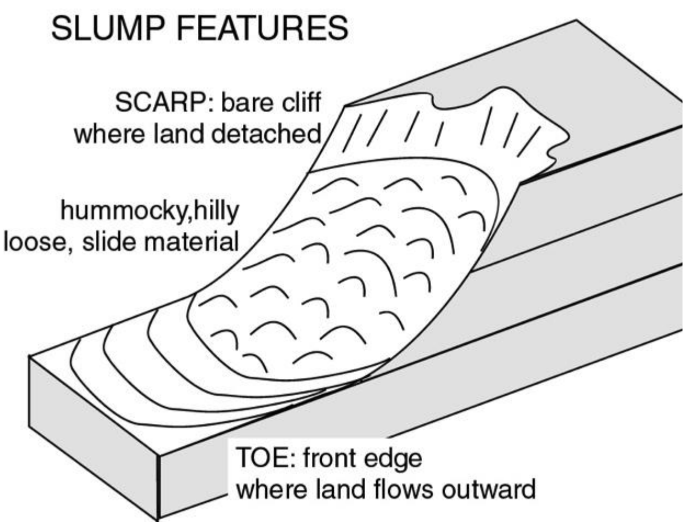
The beds to the left have dips that change from one side of the structure to the other. But the strikes are all the same: N0E. The East limb of the anticline dips 15 to 40°E. The opposite limb dips 15 to 40°W. In the center of the hinge axis, the beds become horizontal with a dip of 0°. So one bed can have multiple dips, depending on where it is in the fold. Geologists indicate these changing dips on a map with multiple attitude marks.

Topography ≠ Geology

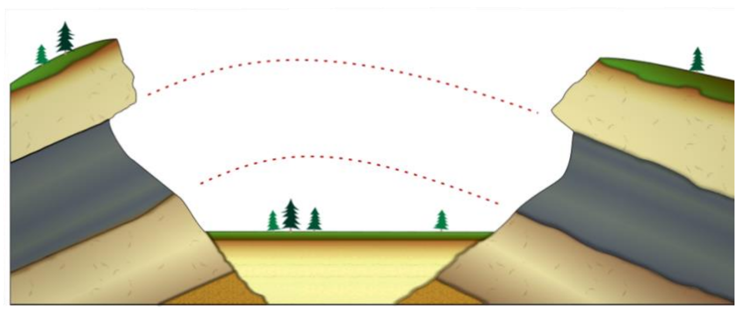
Topography and underlying geology are separate characteristics of a region. For example, in the images below, you can see that, for the image on the left, rivers can carve a valley INTO a geologic anticline or dome. Similarly, for the image on the right, as resistant beds are less easily eroded, it's possible to erode around a resistant bed creating a hilltop or mesa topographically, while geologically, it's a syncline or basin.







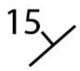
In the above block diagram of a slump, the beds are horizontal, but the topography is a steep hill at the top of the landslide; hummocky, irregular topography in the middle of the landslide; and a gentle slope at the toe of the landslide. These slopes are independent – separate – from the underlying geology. The dip of the beds (O°) is not the same as the gradient of the hillside.



Cross section showing Steno's principle of horizontal continuity of sedimentary rock strata. Note that the original structure was an anticline, and it is now, topographically, a valley between two hills.
Image: Woudloper – Public Domain

Review the attitude symbols below – indicating orientation in space of different types of rock layers, faults, and folds. You need to use and recognize these in this lab.

PLEASE NOTE: the symbols below are generic, to give you an idea of shape.
Each symbol, when placed or viewed on a map has to be rotated so the strike line is parallel to the strike of the bed, fault, fold hinge axis, etc.

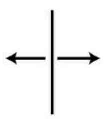


Strike and dip of rock layer
(strike: N45E; dip: 15 NW)

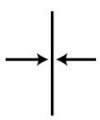
Strike and dip of vertical rock layer
(strike: N45E; dip: 90)

Strike and dip of overturned rock layer
(strike: N45E; dip: 80SE)

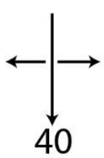
Strike and dip of horizontal rock layer
(strike: n/a; dip: 0)



Axis of an anticline



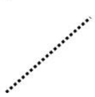
Axis of an syncline



Axis of an anticline
plunging 40 degrees

Rock formation contact *(known)*

Rock formation contact *(approximate)*

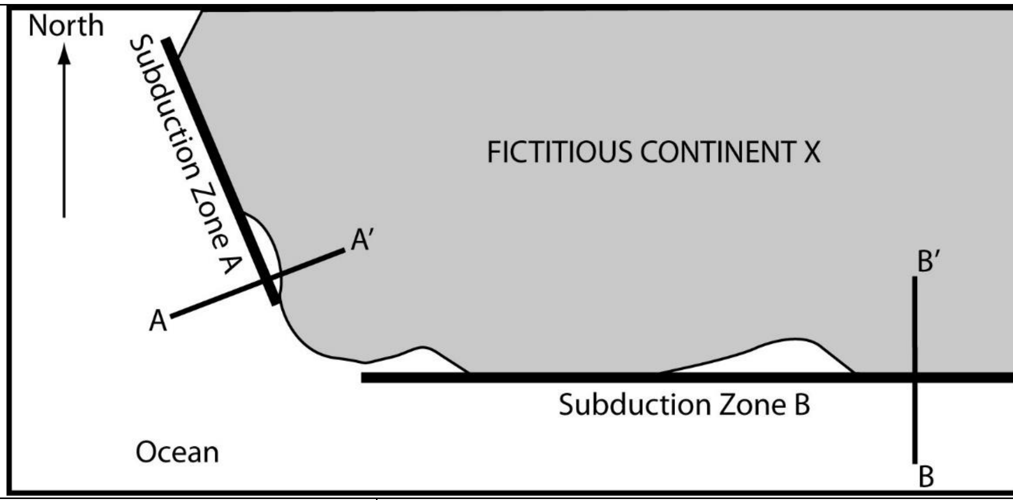


Rock formation contact *(inferred)*

Structural Geology Prereading Homework

Strike is the orientation of the line that forms where a dipping planar surface intersects a horizontal planar surface, such as the location on a map where oceanic lithosphere is subducting. (To record strike, we use the geologist orientation standard: NX°W or NX°E +/-Y°, where X ≤ 90°.)

The figure to the right shows a "Map View" of two subduction zones (A and B). Note: A-A' and B-B' cross-section lines, which show the location of cross section shown in questions 3 and 4. Cross sections illustrate what the plate is doing underground. Use the map to the right to understand the orientation of these two subduction zones.

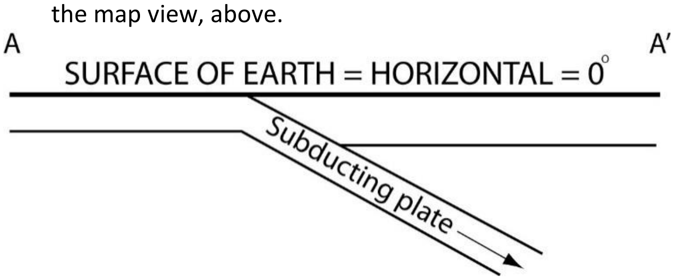


1. Measure the strike of subduction plate A from the map view above.

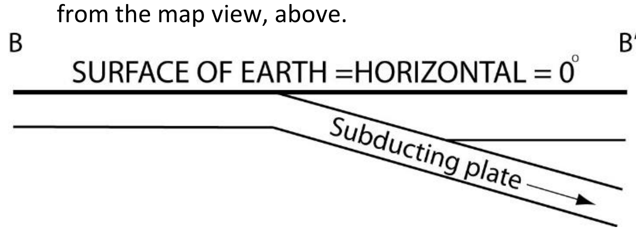
2. Measure the strike of subduction plate B from the map view above.

Dip is a measurement of how much a planar or semi planar object (like a tectonic plate or a layer of rock) slopes below a horizontal surface. A direction is associated with the dip, indicating which direction it is dipping underground (the same direction that water would run, if allowed to run down the planar face). For example, a subductions where the subducting plate dips 45° +/-2° under the surface, and water would run down toward the northwest sector, we would say it has a dip of 45°NW +/-2°. Note: Vertical surfaces have a dip of 90°, and hence no direction – water would run down only.

3. Measure the dip of subduction plate A from the cross section (A-A') below, and determine the dip direction from the map view, above.



4. Measure the dip of subduction plate B from the cross section (B-B') below, and determine the dip direction from the map view, above.



5. What is the strike and dip of a vertical wall that is aligned East – West?

6. What is the strike and dip of a vertical wall that is aligned North – South?

7. Draw the attitude symbol for the above wall.

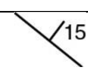
8. Draw the attitude symbol for the above wall.

9. What is the strike and dip of a perfectly flat floor?

10. Draw the attitude symbol for the floor.

11. Draw the attitude symbol of a bed with this orientation: N30°E 45°SE

12. What are the correct strike and dip values that correspond to this attitude marker?



Structural Geology Lab Exercises

INSTRUCTIONS For ALL box diagrams:

1. First record the page number on the back, center of the diagram (you will have more success and work faster if you proceed through the diagrams in the order given – easiest to hardest).

NOTE: The last two diagrams are beyond the level for which you will be responsible on the exam. Complete these only to push yourself and your understanding.

2. Cut around the outline of each box. **Cut along one additional edge of each corner square** (so you can bend and fold corners under box, as you build it). Fold along lines and turn into a 3-D box. *(You can tape the edges of the box together, so it stands, but you'll need to remove the tape to make your drawings, so don't use permanent tape.)*
3. Add North Arrow pointing to top of page.
4. Complete all blank sides on the box diagram.
   - Beds should be the same thickness everywhere in the drawing.
   - Sometimes evidence for underlying beds exists elsewhere in your drawing. Pay attention.
   - ***Use dashed lines when you are making up the base of a layer because there's no data to confirm it..*
   - Strike and dip markers (attitudes) exist ONLY where rocks outcrop at the surface and can be measured. Rock layers that don't have attitude markers in them will still do the same things that the rocks above and below them in the sequence will do. So use the attitude marks you DO have to see what is happening to all the rocks.

EXTRA INSTRUCTIONS for first box diagram only:

THESE ARE NOT REAL ROCK LAYERS – THIS EXERCISE IS JUST FOR PRACTICE MEASURING STRIKE AND DIP, DRAWING ATTITUDE MARKERS, AND IMAGINING A LAYER IN 3-D. These beds would never co-exist as they do in this box diagram.

1. Treat each rock layer independently.
2. Add correct attitude markers to the top of the box for each bed.

****REMEMBER: attitudes marks go IN the bed they reference, not along side it!****

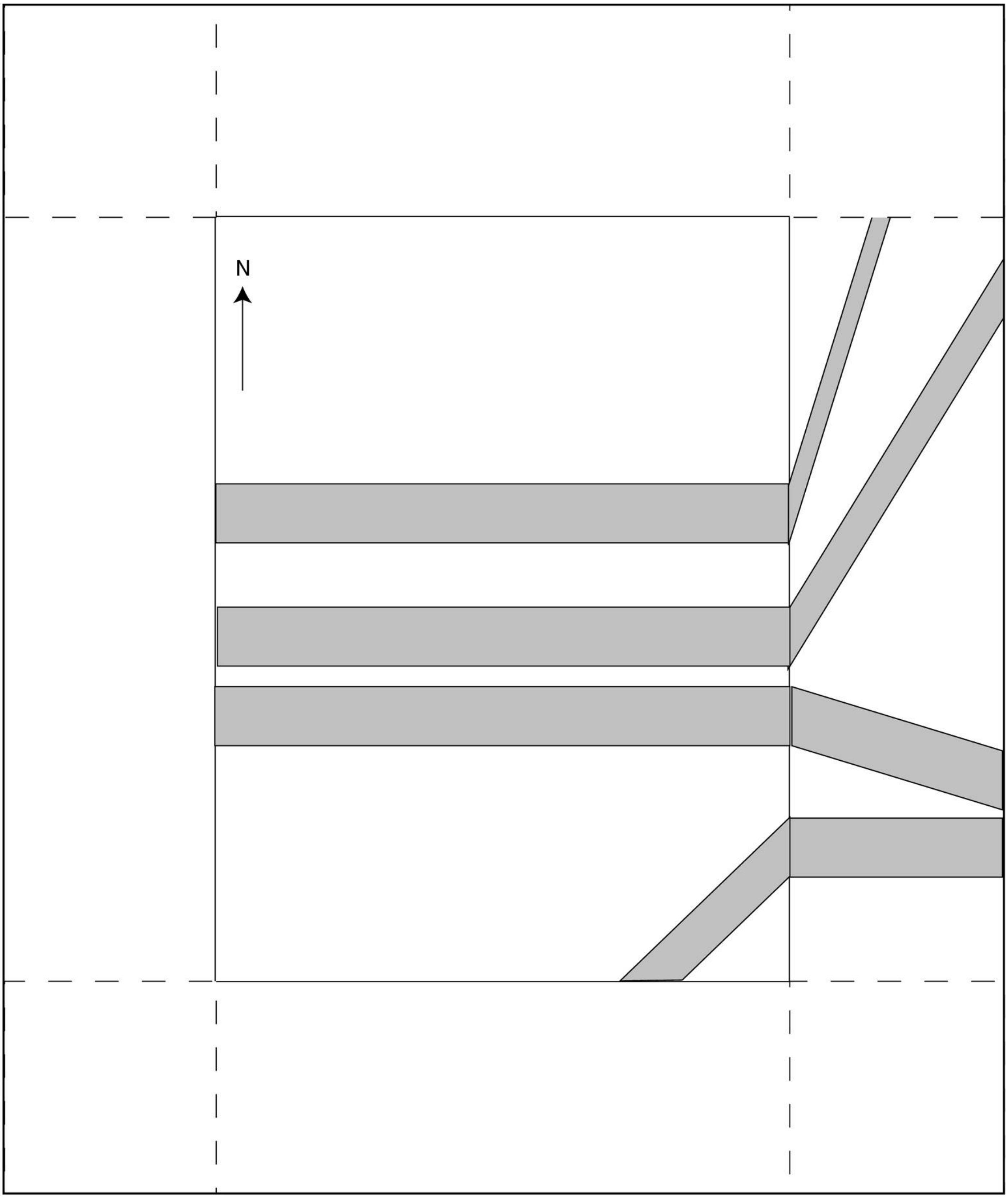
EXTRA INSTRUCTIONS for all remaining box diagrams:

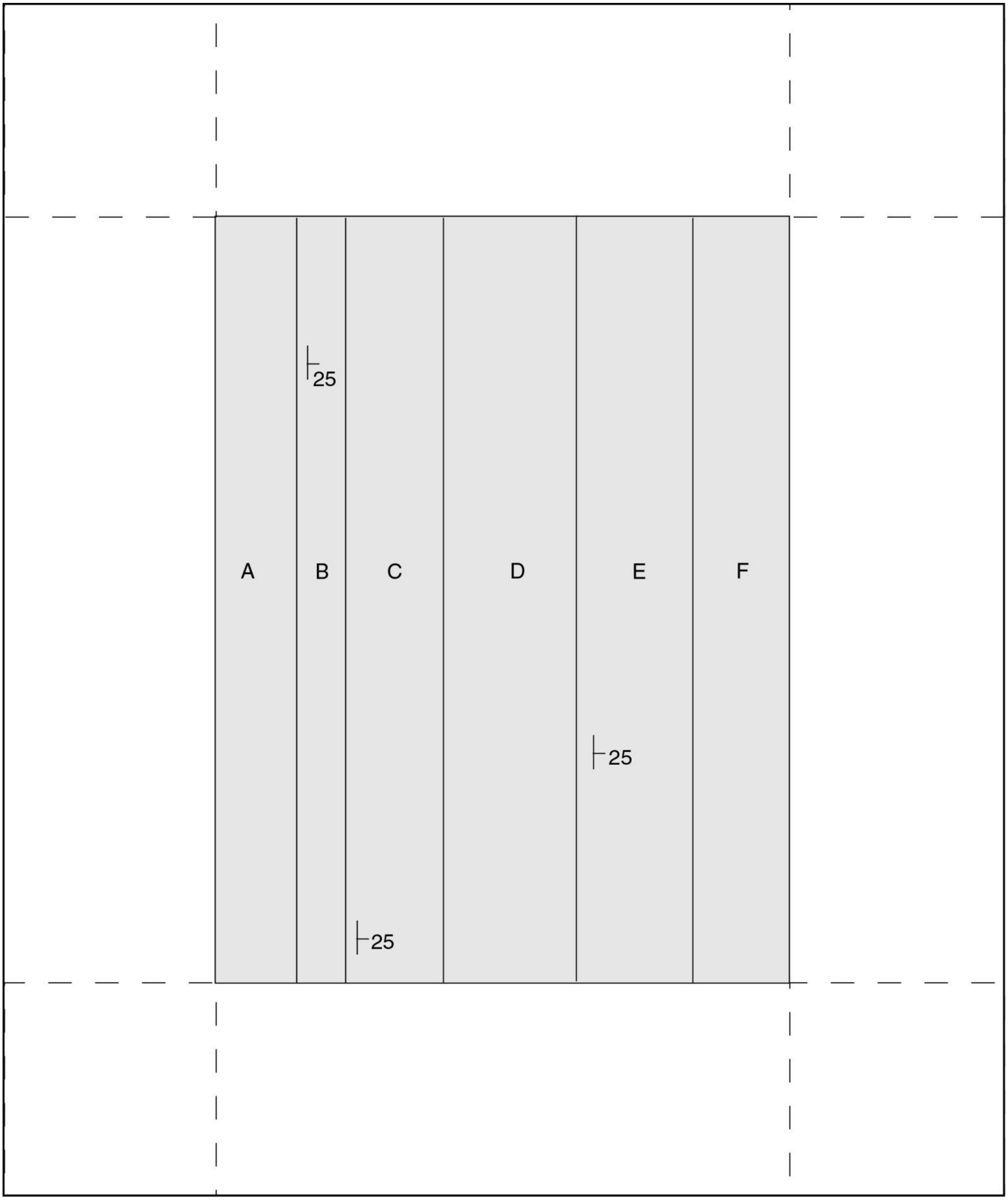
ALL BEDS ARE SEDIMENTARY ROCK LAYERS LAID DOWN ORIGINALLY HORIZONTALLY.

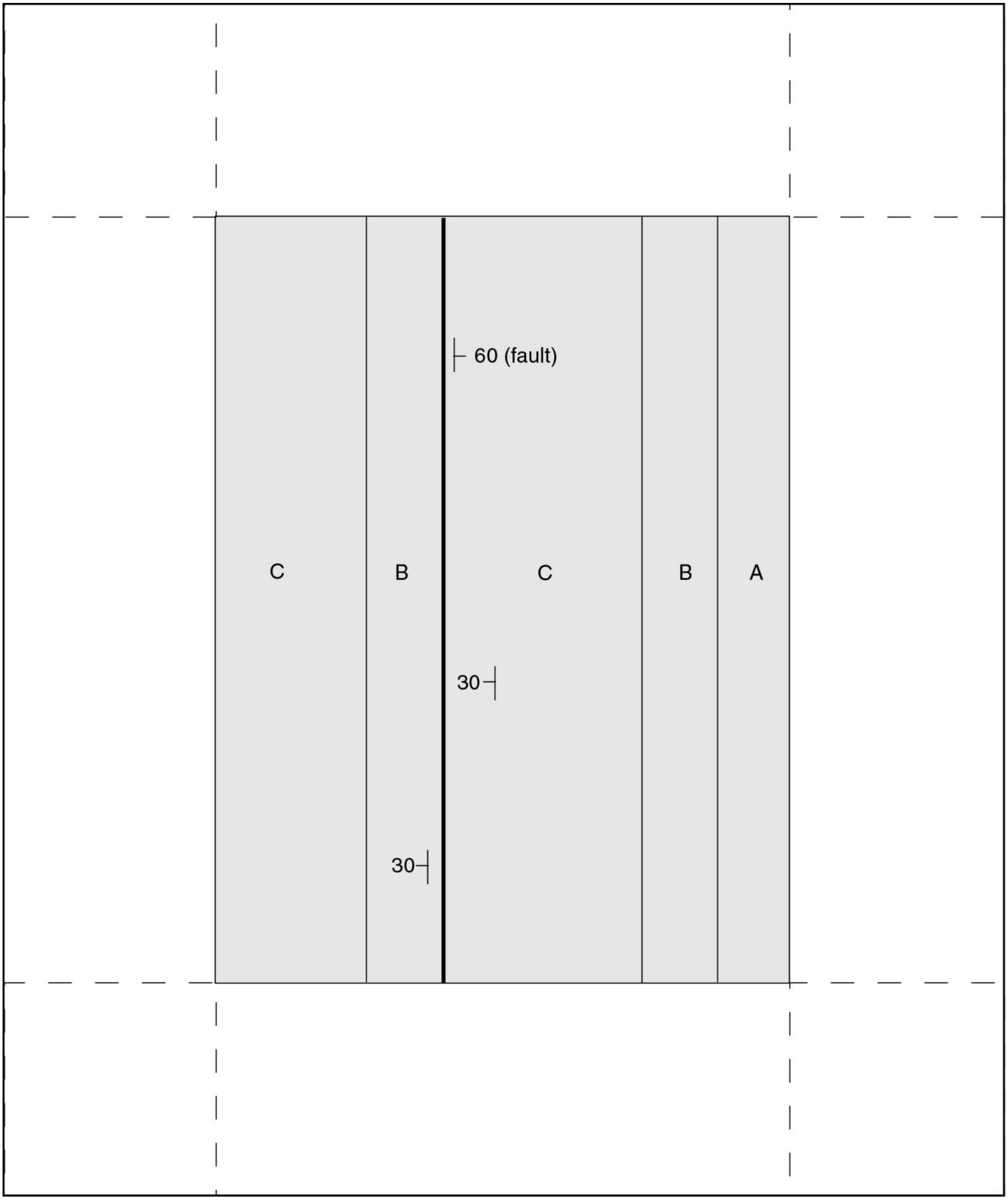
1. Label all layers in increasing age (1=youngest).
2. Where **faults** exist, on the back of the diagram, identify *fault type* and *stress type*. On the front of the diagram, where appropriate, *add arrows to indicate relative motion*.
3. Where **folds** exist, on the back of the diagram, identify *structure*. On the front of the diagram, draw in the *hinge axes*, appropriate *fold arrows* relative to hinge axis, *plunge symbols,* and *plunge values*.
   - Hinge lines have arrows on their ends only when they are plunging.
   - The fold axis bisects the structure completely.

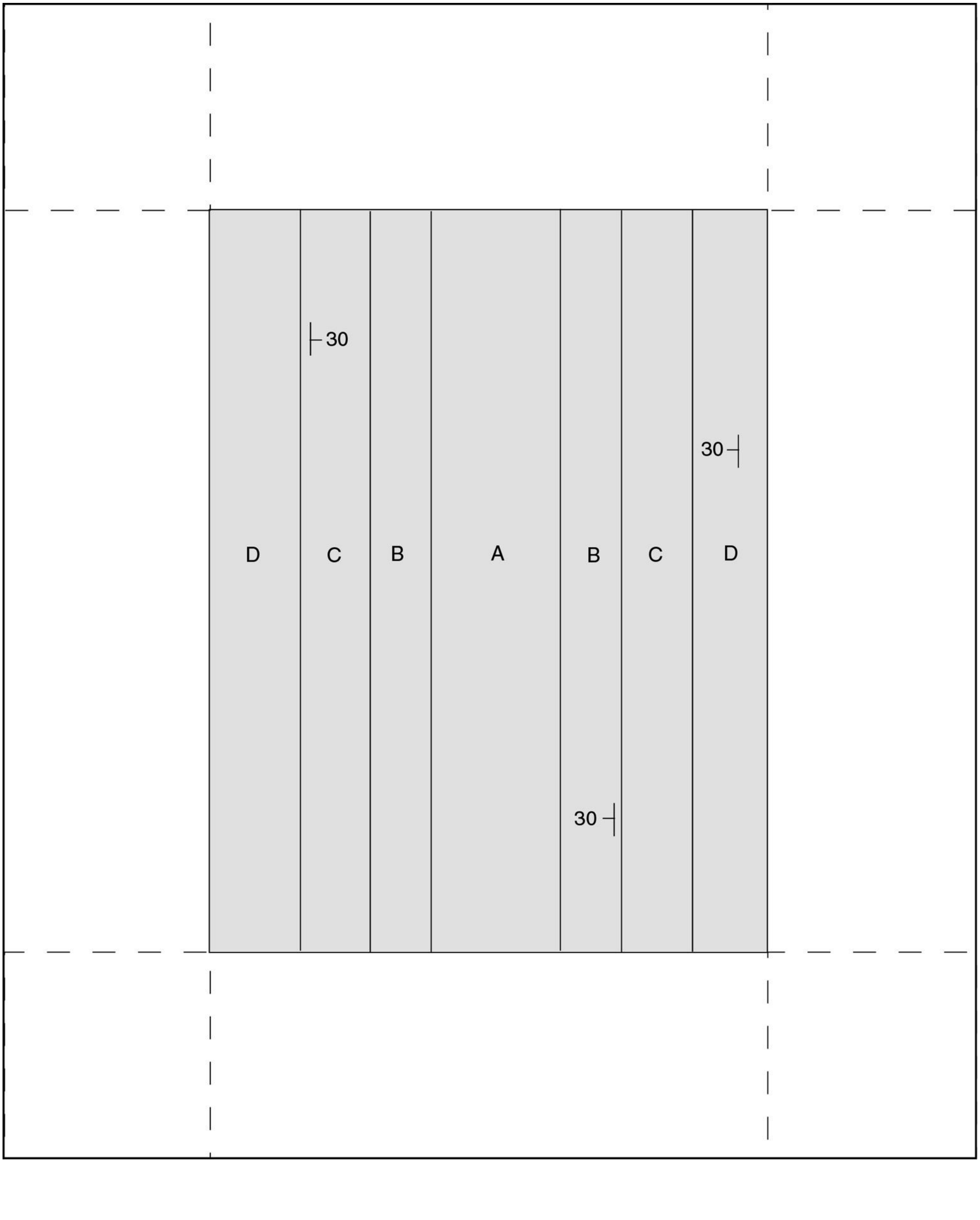
Remember these pointers:

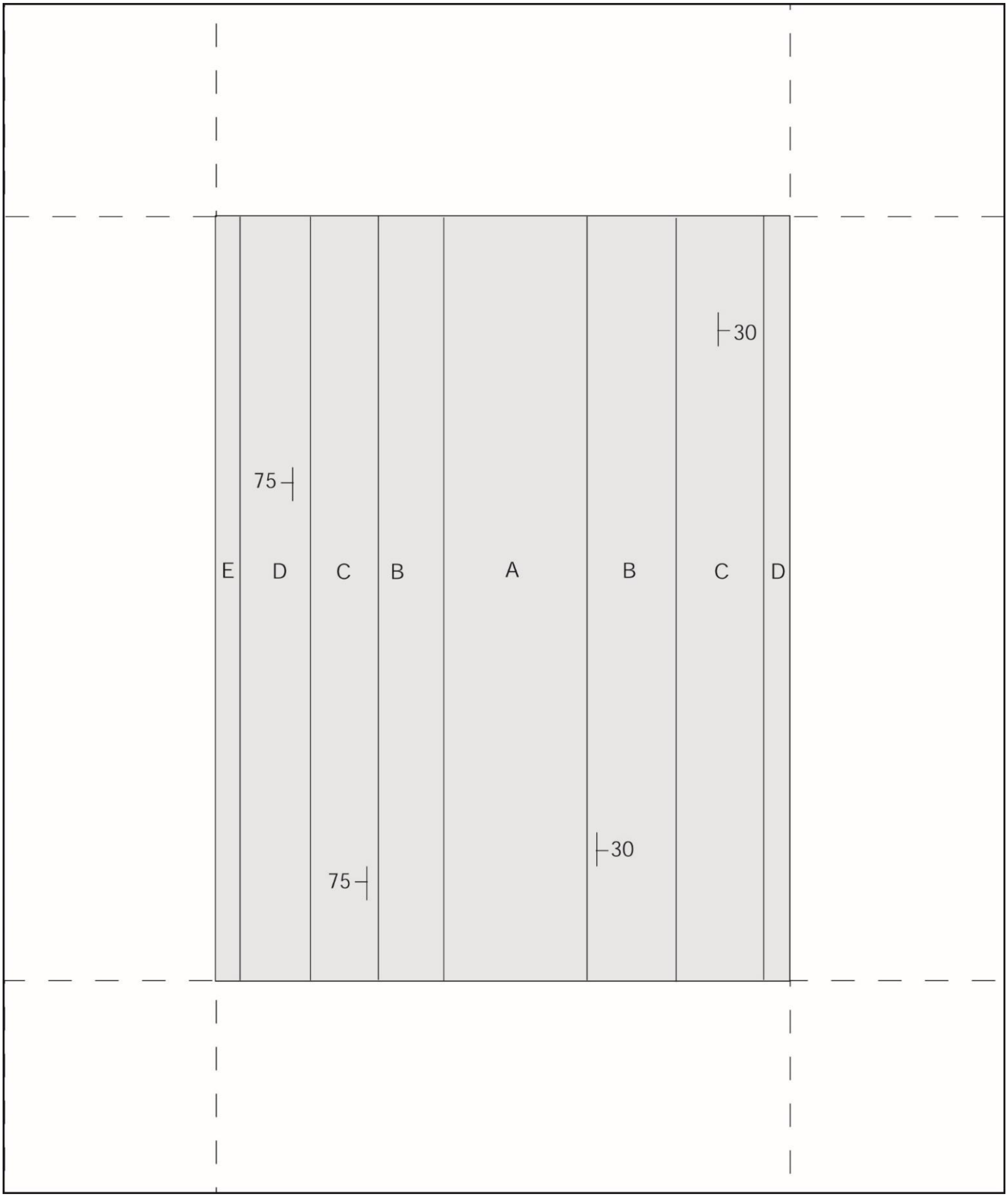
- Measure strikes and dips carefully (with a protractor).
- Use colored pencils to help distinguish beds (suggestion only; not required).
- Beds of the same letter are the same! Make sure they are continuous (connect).
- Stratigraphy (relative order of beds) should be the same throughout your drawing!


N

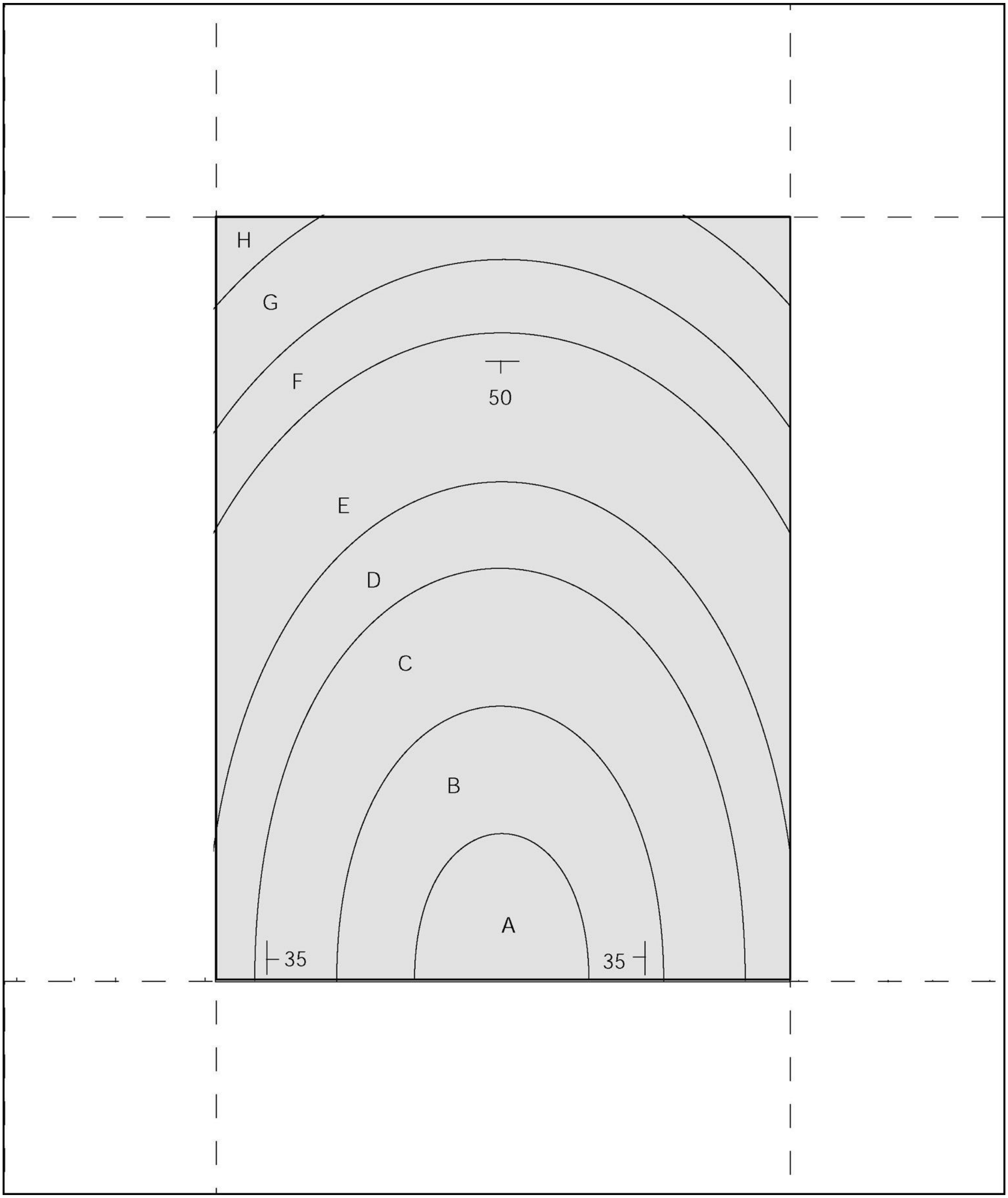

25
A
B
C
D
E
F
25
25

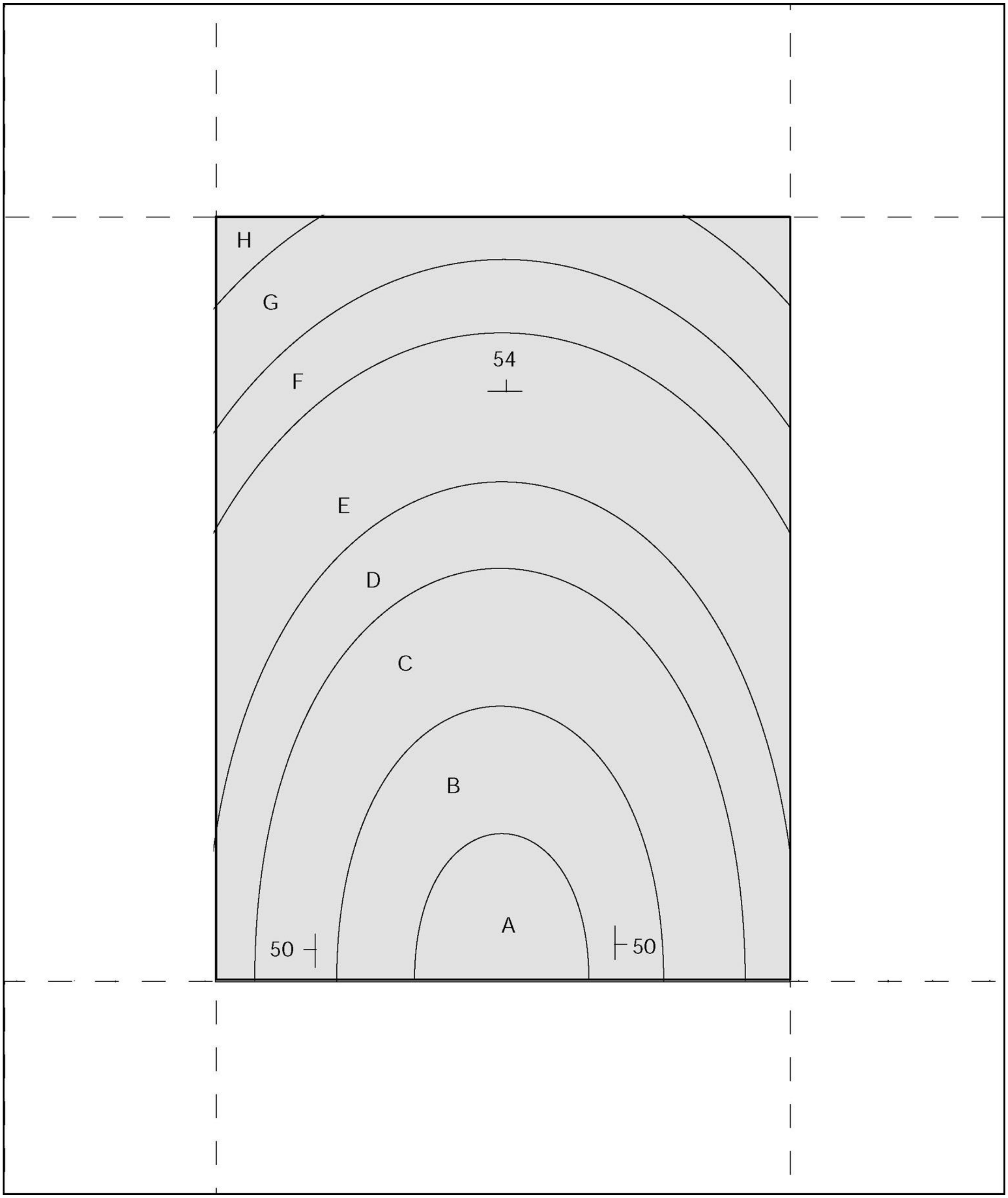

60 (fault)
C
B
C
B
A
30
30


30
30
D
C
B
A
B
C
D
30

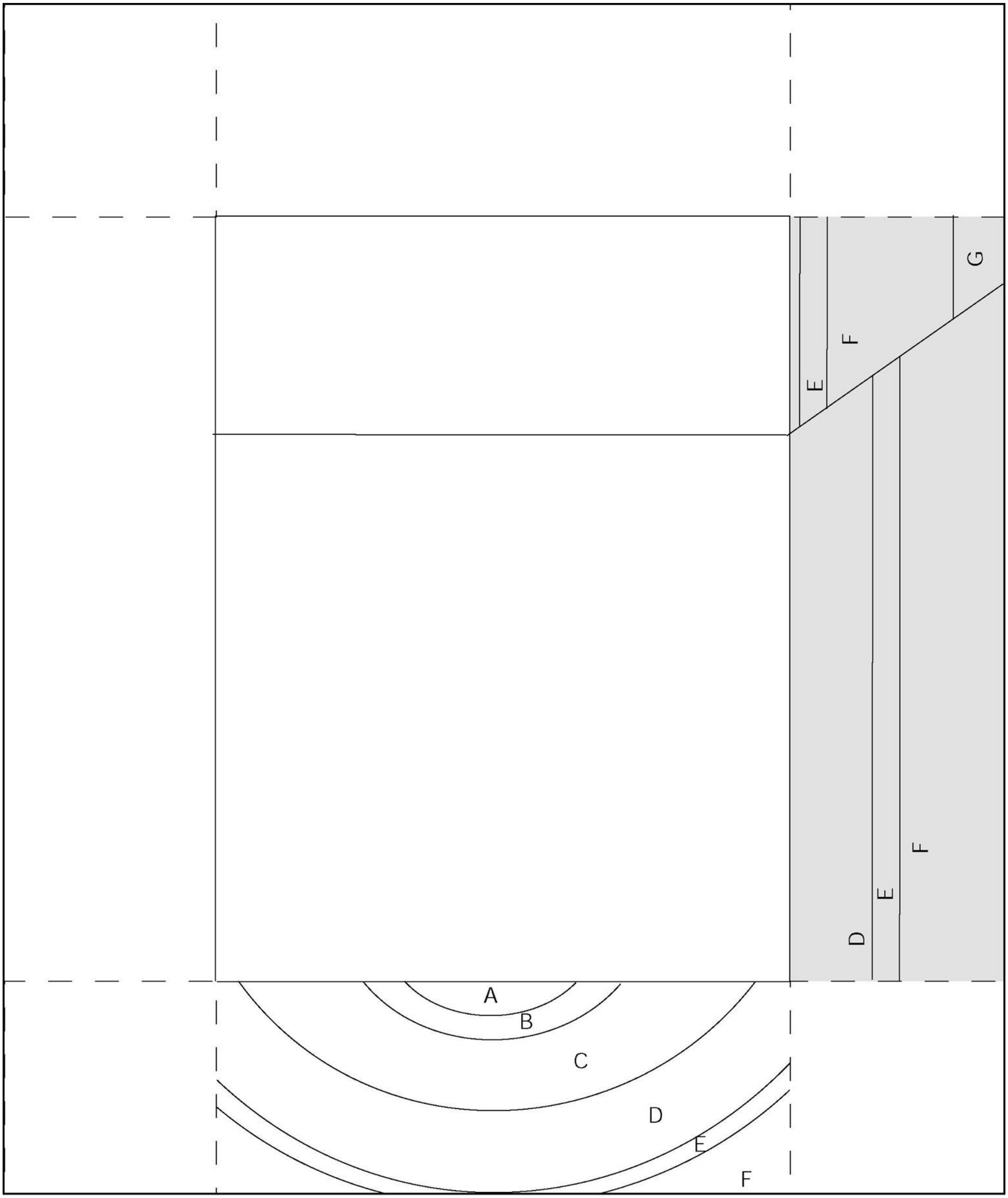


30
75
E
D
C
B
A
B
C
D
30
75

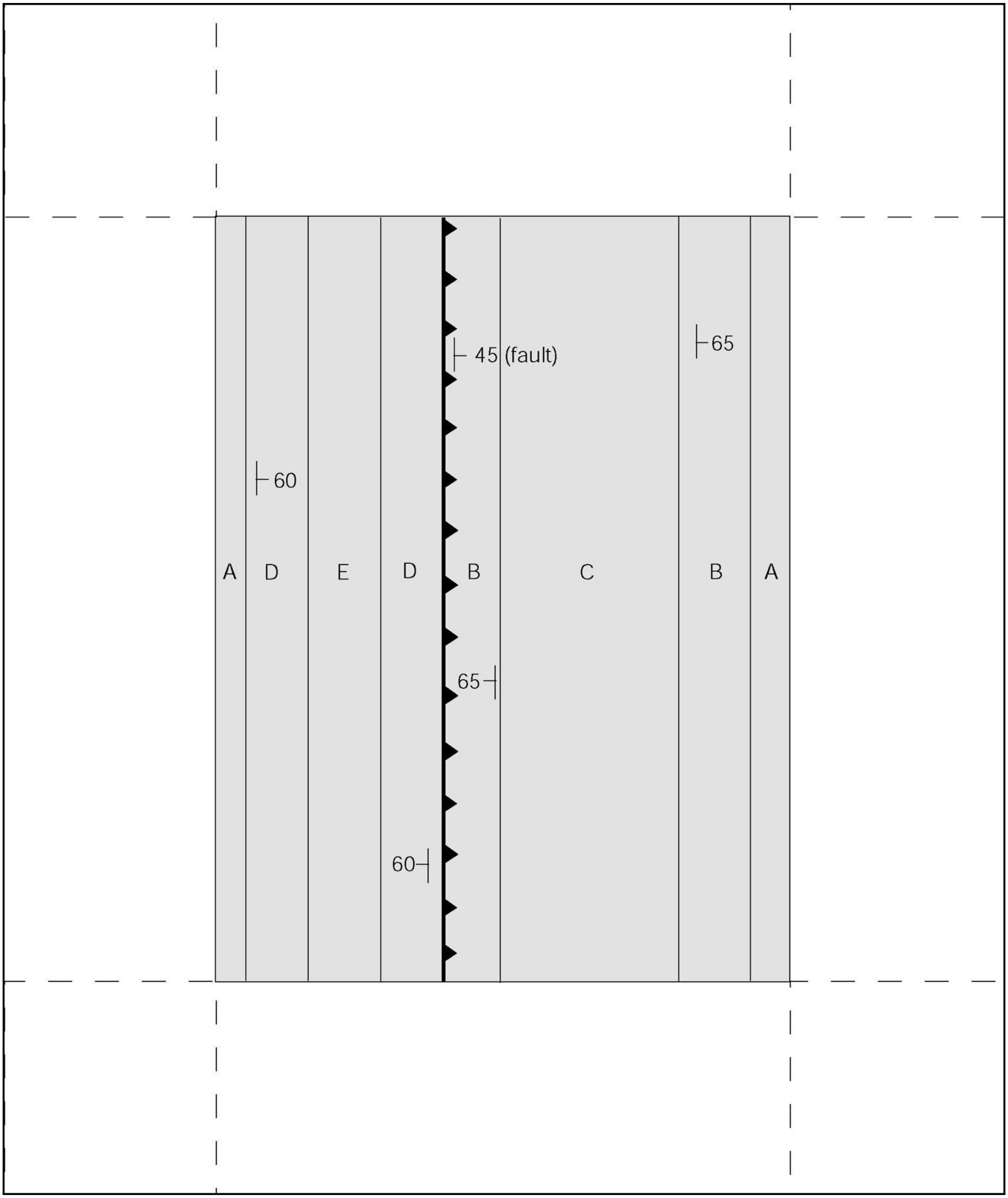

H
G
F
50
E
D
C
B
A
35
35


H
G
F
54
E
D
C
B
A
50
50

NOT REQUIRED FOR LAB – EXTRA WORK FOR ADVANCED UNDERSTANDING ONLY



NOT REQUIRED FOR LAB – EXTRA WORK FOR ADVANCED UNDERSTANDING ONLY



Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

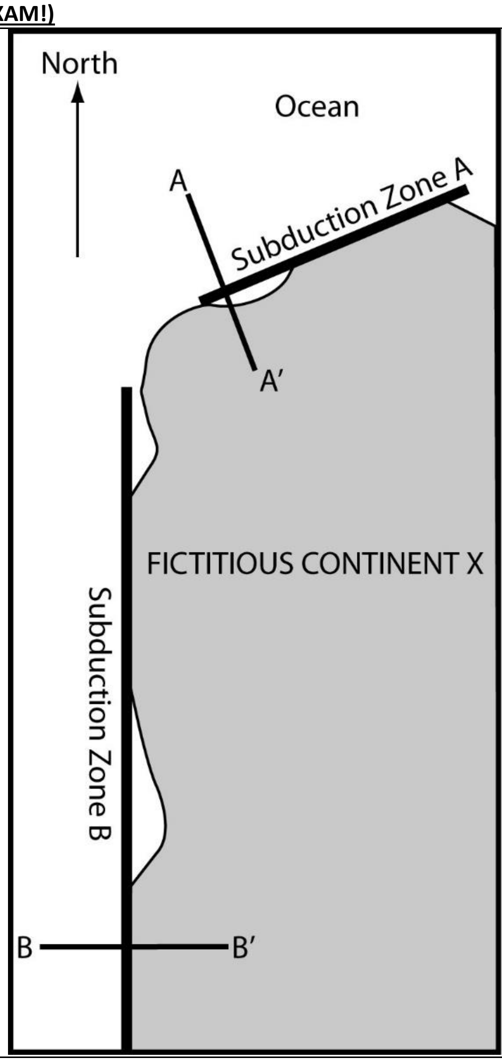
Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Identify, interpret, and create strike and dip symbols on a geologic map surface.	A | B | C | D | F	
Generate 3D models of subsurface geology based on surface strike and dip data.	A | B | C | D | F	
Accurately identify and name folds and faults found on Earth's surface based on 3D models.	A | B | C | D | F	
Evaluate the relative age (oldest to youngest) of layered rocks that have been tilted, folded, or faulted.	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

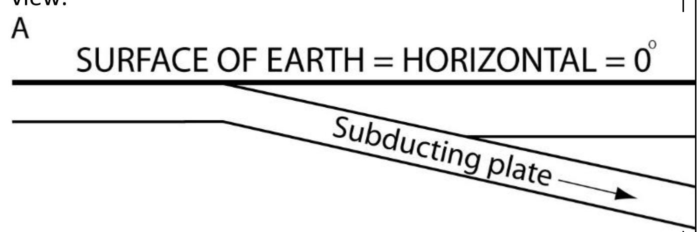
Structural Geology Practice Sheet

Remember – the exam questions come directly from the labs, so to do well on the exam, be sure to study ALL the questions on the labs and be able to correctly answer them on the exam. To assist, this study sheet gives you a chance to practice SOME of the skills from recent labs. BE CAREFUL – just because a question appears on this sheet doesn't mean it will show up on the exam and just because a questions doesn't appear on this Practice Sheet doesn't mean that it won't show up on the exam. To be sure you're thoroughly prepared, study all questions from recent labs. Just like on the exam, **show ALL work.** (You may use a calculator.) **(BRING PENCILS, COLORED PENCILS, ERASERS, PROTRACTORS, TRIANGLES, AND SCISSORS TO THE EXAM!)**



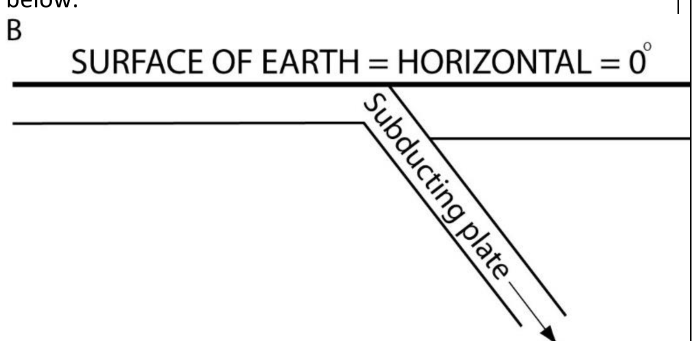
1. Measure the strike of subduction plate A.

2. Measure the dip of subduction plate A from the cross section (A-A') below, and determine the dip direction from the map view.



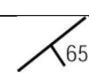
3. Measure the strike of subduction plate B.

4. Measure the dip of subduction plate B: cross-section shown below.



5. Draw the attitude symbol of a bed with this orientation: N60°W 12°SW

6. What are the correct strike and dip values that correspond to this attitude marker?

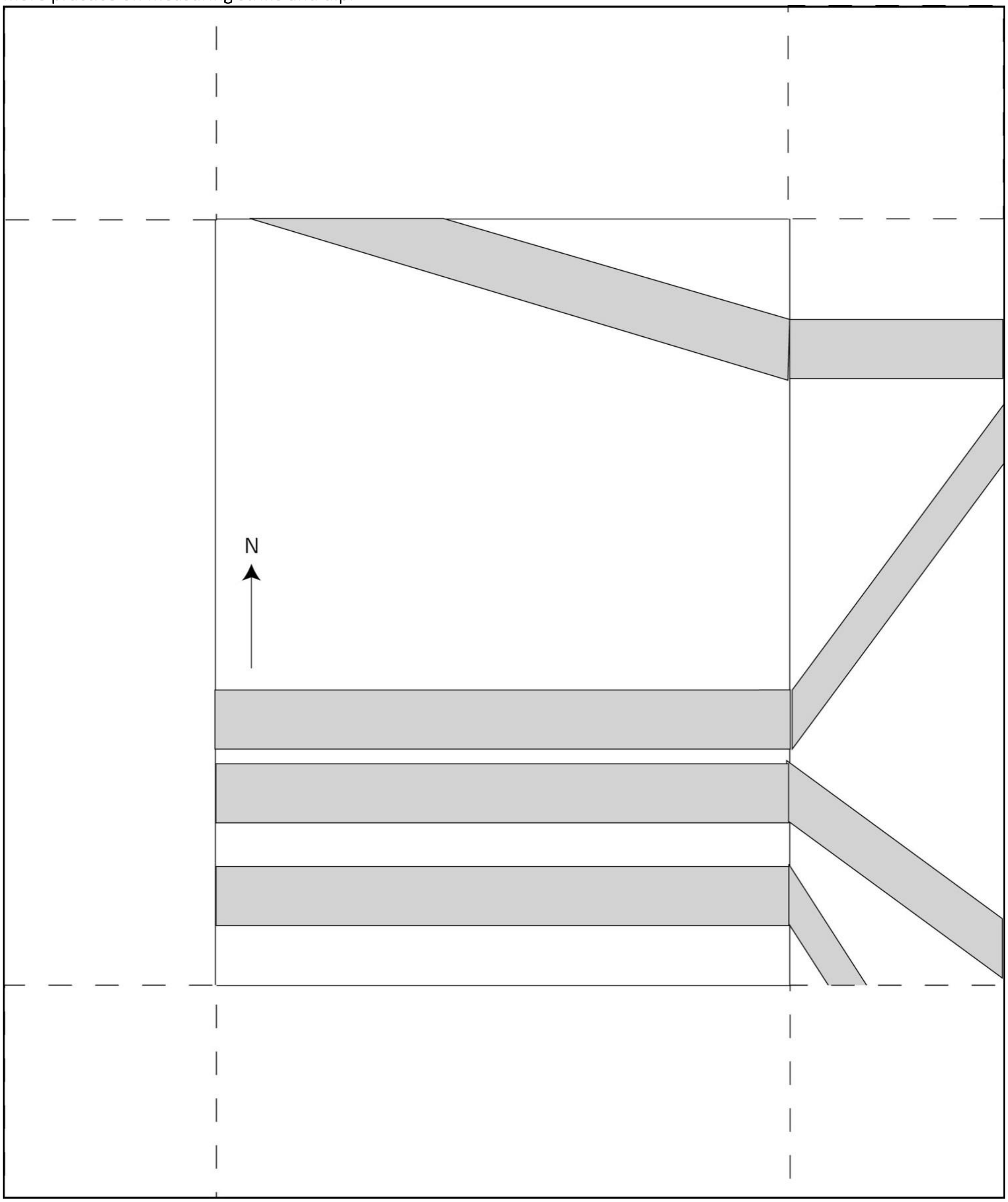


7. If you see a horseshoe-shaped outcrop pattern on the surface open to the east, and the beds are dipping into the center, what kind of structure are you observing? (Be as thorough as you can!)

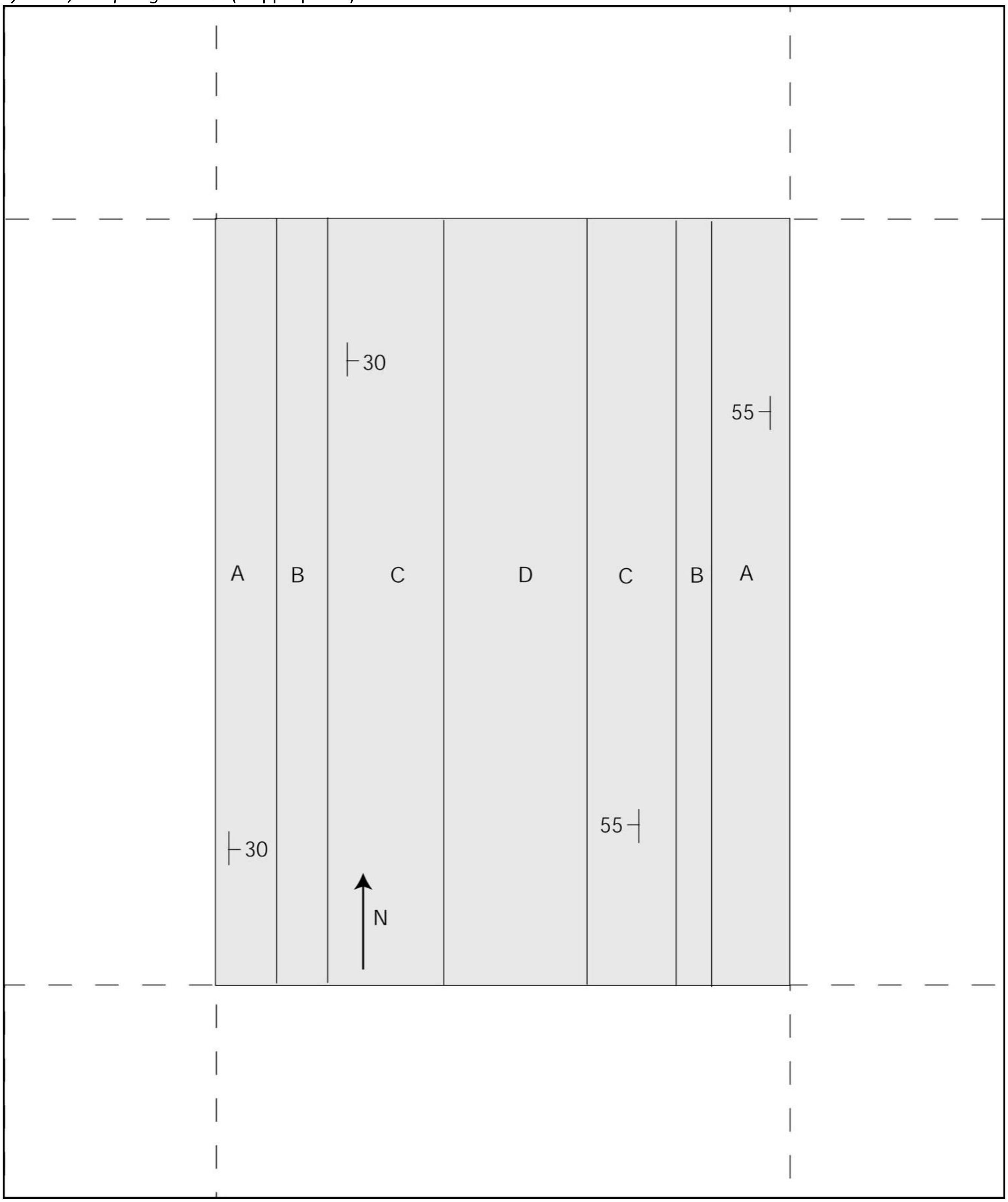
8. Where do you find the oldest rocks on the surface of such a fold?

Add correct attitude markers to the top of the box for each bed.

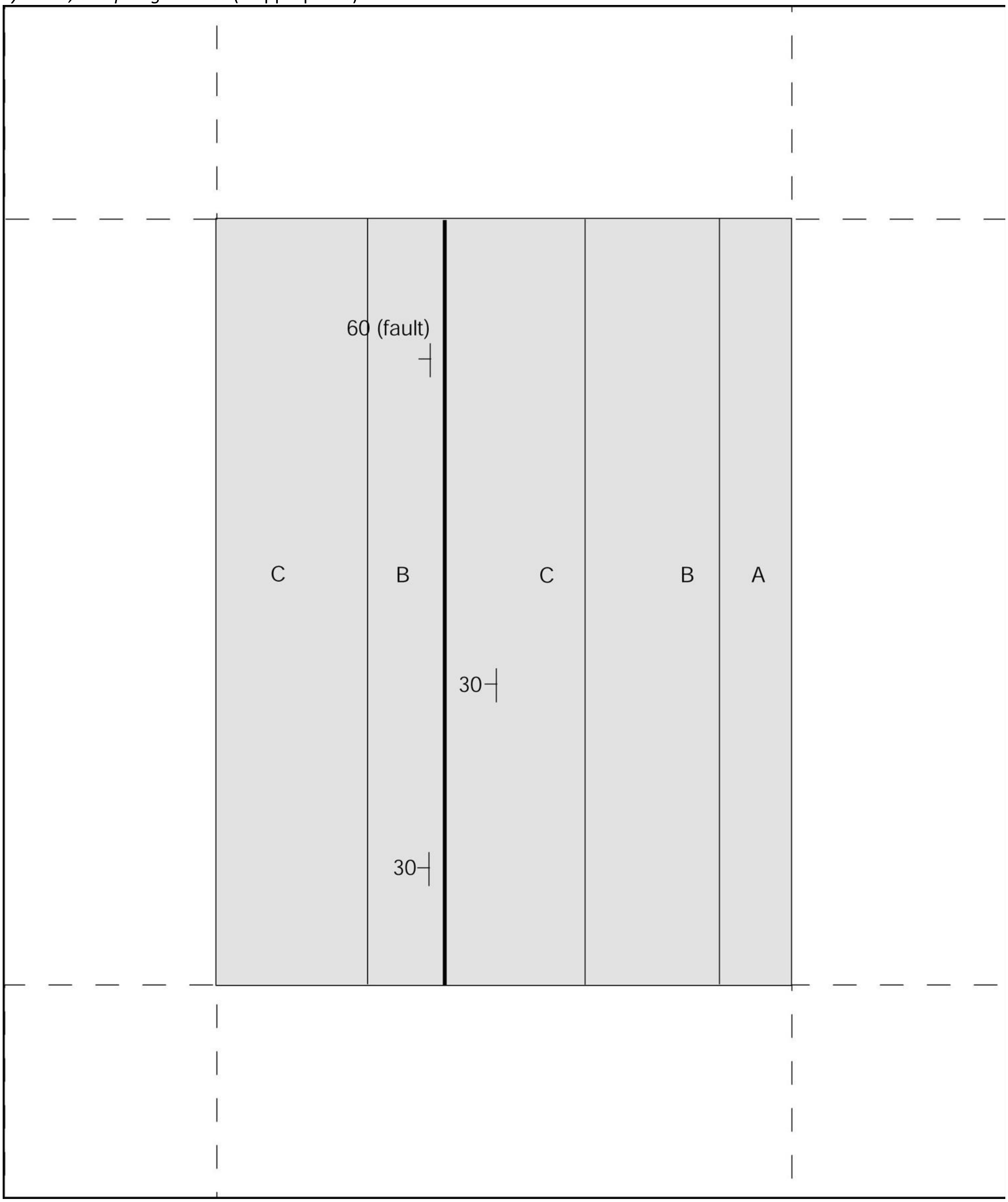
NOTE: These beds would never co-exist as they do in this box diagram. The situation is fictitious – meant only to give you more practice on measuring strike and dip.



Complete all blank sides on the box diagram.
Label all layers in increasing age (1=youngest).
Where **faults** exist, on the back of the diagram, identify *fault type* and *stress type*. On the front of the diagram, where appropriate, *add arrows to indicate relative motion*.
Where **folds** exist, identify *structure*. Draw in the *axial plane*, appropriate *fold arrows* relative to hinge axis, *plunge symbols,* and *plunge values* (if appropriate).

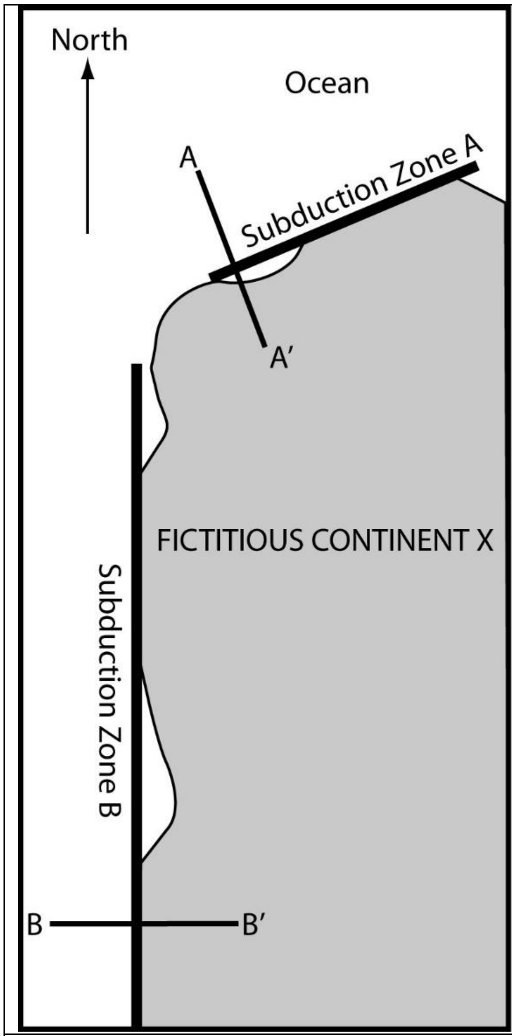


Complete all blank sides on the box diagram.
Label all layers in increasing age (1=youngest).
Where **faults** exist, on the back of the diagram, identify *fault type* and *stress type*. On the front of the diagram, where appropriate, *add arrows to indicate relative motion*.
Where **folds** exist, identify *structure*. Draw in the *axial plane*, appropriate *fold arrows* relative to hinge axis, *plunge symbols,* and *plunge values* (if appropriate).



LEAVE BLANK FOR USE DURING ONLINE QUIZ/EXAM

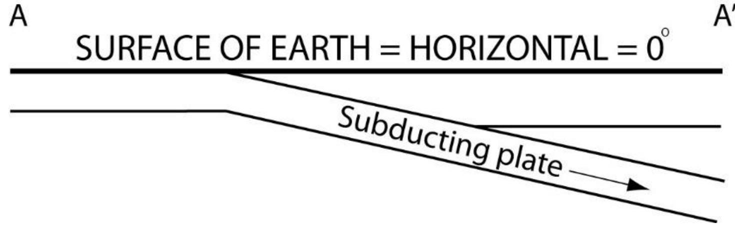
KEY



1. Measure the strike of subduction plate A.

N67E

2. Measure the dip of subduction plate A from the cross section (A-A’) below, and determine the dip direction from the map view.

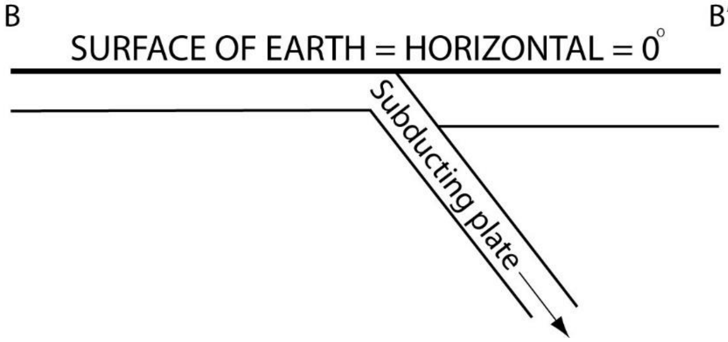


12SE

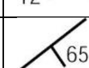
3. Measure the strike of subduction plate B.

N0E or N0W

4. Measure the dip of subduction plate B: cross-section shown below.

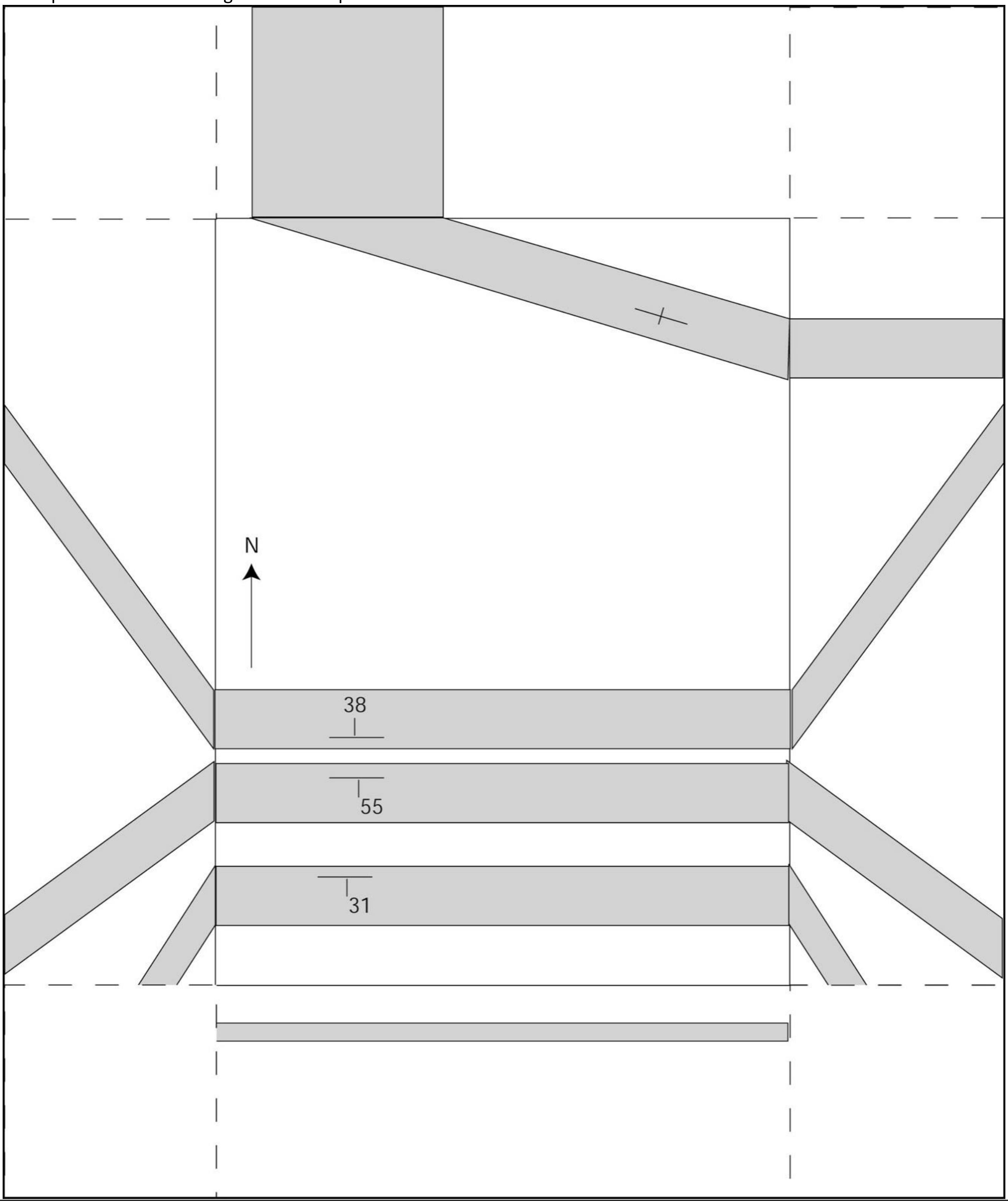


51E

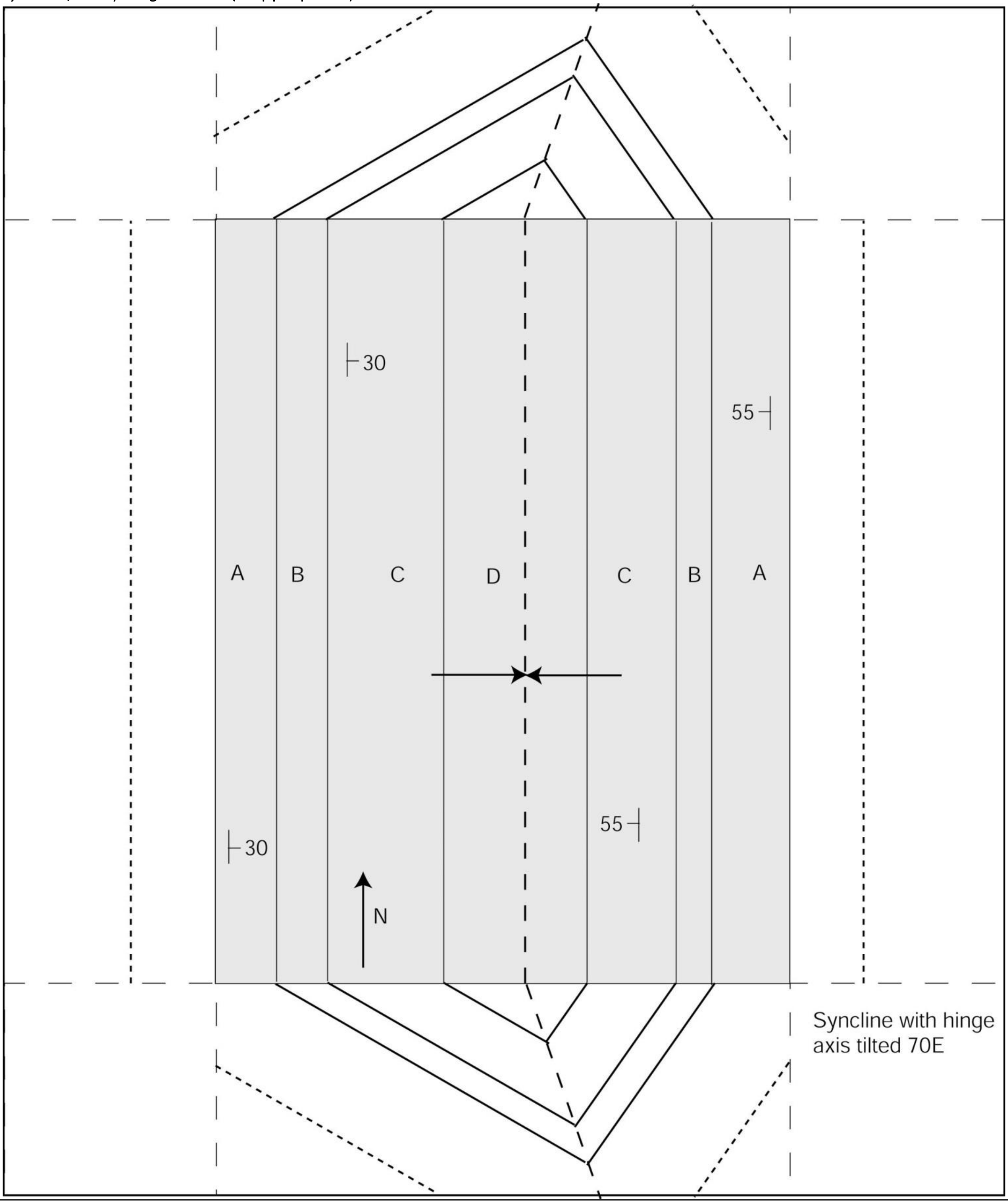
5. Draw the attitude symbol of a bed with this orientation:	 N60°W 12°SW
6. What are the correct strike and dip values that correspond to this attitude marker?	 N52E 65SE
7. If you see a horseshoe-shaped outcrop pattern on the surface open to the east, and the beds are dipping into the center, what kind of structure are you observing? (Be as thorough as you can!) ***East-plunging syncline***	8. Where do you find the oldest rocks on the surface of such a fold? ***Edges***

9. Add correct attitude markers to the top of the box for each bed.

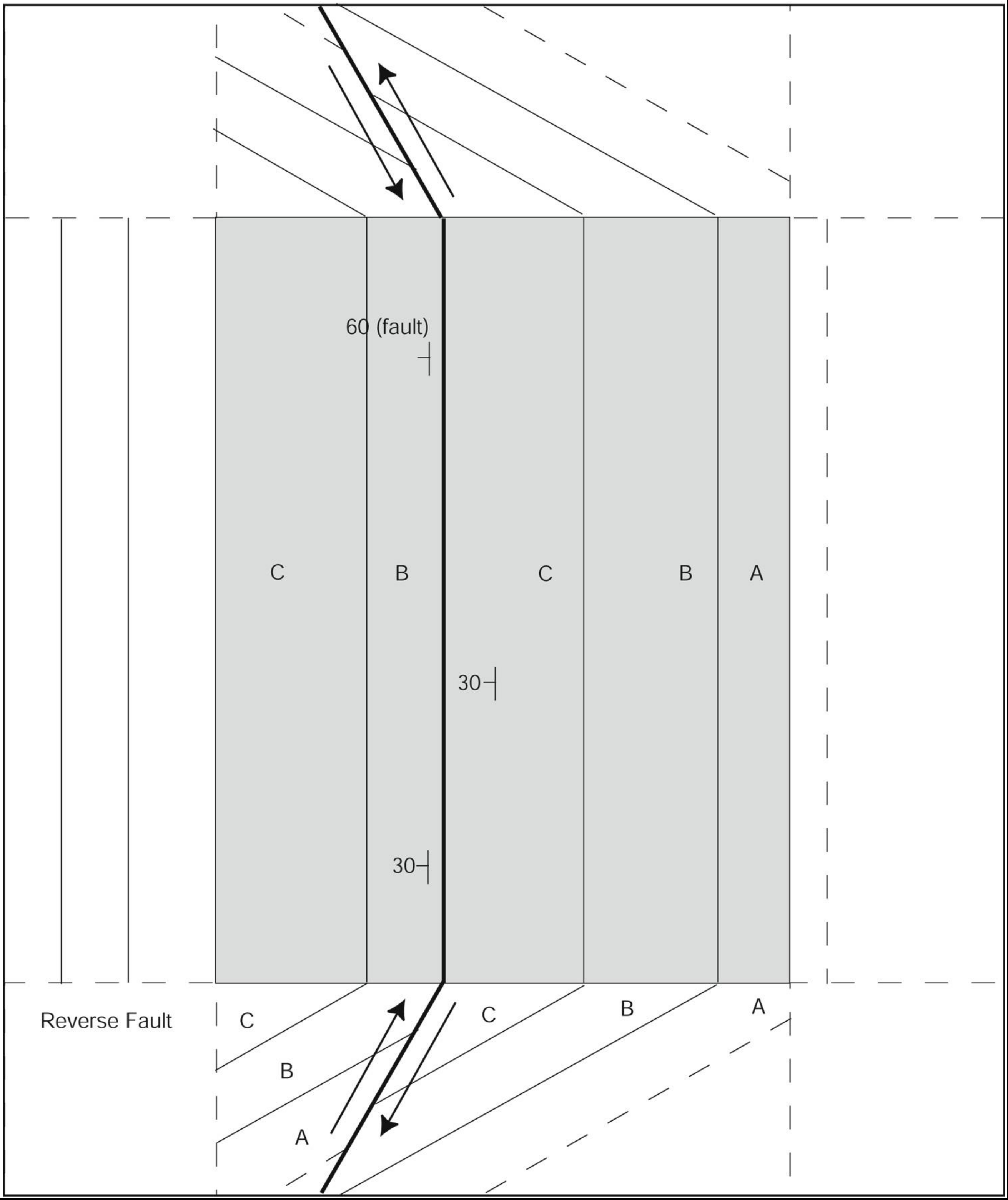
NOTE: These beds would never co-exist as they do in this box diagram. The situation is fictitious – meant only to give you more practice on measuring strike and dip.



10. Complete all blank sides on the box diagram.
Label all layers in increasing age (1=youngest).
Where **faults** exist, on the back of the diagram, identify *fault type* and *stress type*. On the front of the diagram, where appropriate, *add arrows to indicate relative motion*.
Where **folds** exist, identify *structure*. Draw in the *axial plane*, appropriate *fold arrows* relative to hinge axis, *plunge symbols,* and *plunge values* (if appropriate).



11. Complete all blank sides on the box diagram.
Label all layers in increasing age (1=youngest).
Where **faults** exist, on the back of the diagram, identify *fault type* and *stress type*. On the front of the diagram, where appropriate, *add arrows to indicate relative motion*.
Where **folds** exist, identify *structure*. Draw in the *axial plane*, appropriate *fold arrows* relative to hinge axis, *plunge symbols,* and *plunge values* (if appropriate).

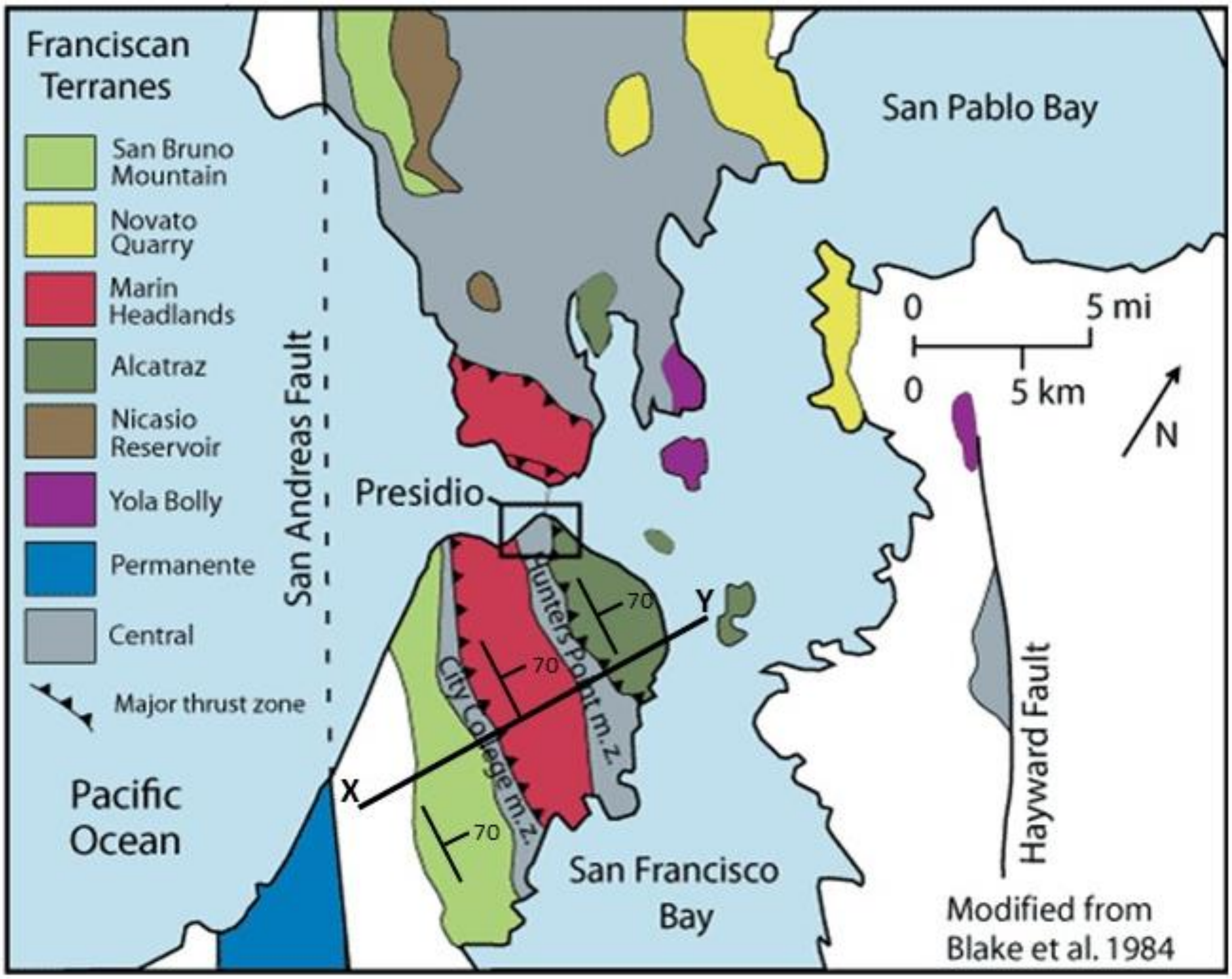


Geologic Mapping and Cross-Sections

NEEDED SUPPLIES:

- Protractor, Ruler, (+ optional drafting Triangles)
- Colored pencils
- Pencil and eraser

To map an area geologically, geologists take 7.5' topographic quadrangles out to the field. They find good rock outcrops, describe the rocks in detail, and measure attitudes of all bedding planes, faults, and joints. They place strike and dip symbols on the map in the correct locations. When two different rock formations come in contact with each other, geologists walk along them, recording the contact location on the map. They record the boundaries of all rock types as precisely as possible on the map. The result:



*Generalized **GEOLOGIC MAP** of San Francisco. Image: Will Elder, National Park Service*

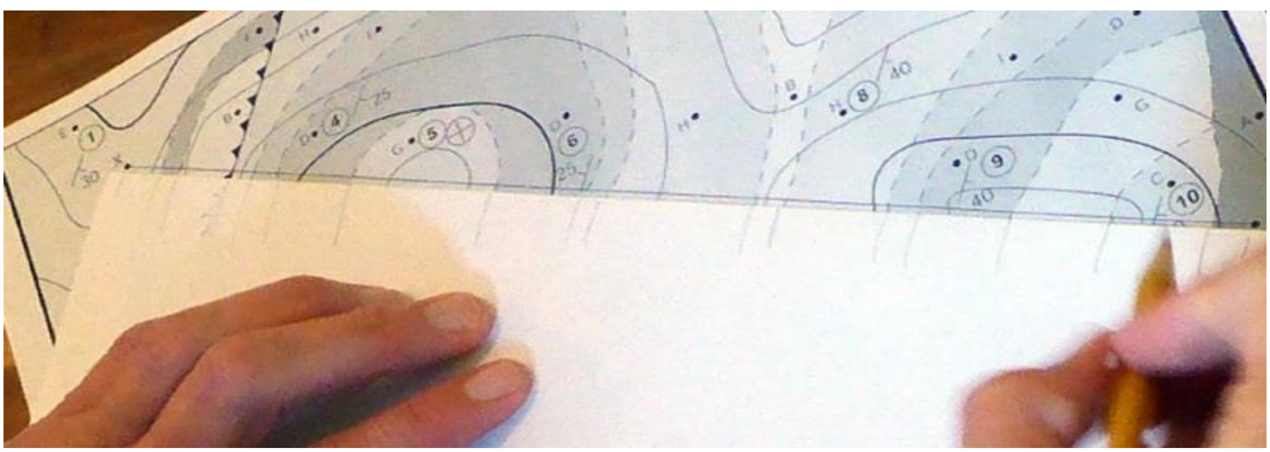
***Notes: The grey "Central" rock unit is found mostly north in Marin and east along the Hayward fault. The grey zones seen in San Francisco are mélange zones (not labeled in the rock unit list on left (the stratigraphy), which is the order of events from youngest at top to oldest at bottom.*

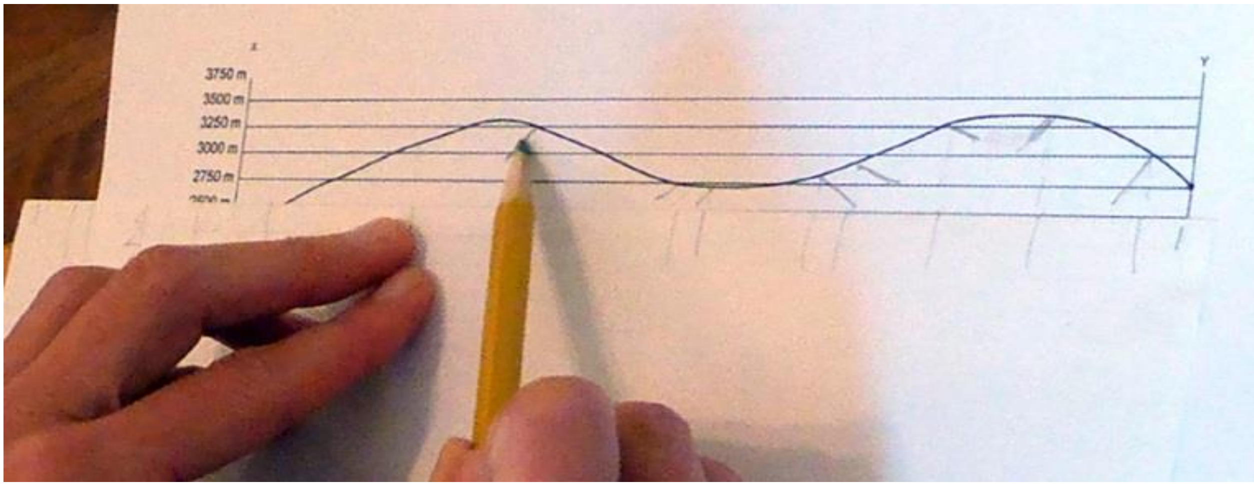
Notice the legend (stratigraphy) that accompanies the map – indicating rock units and relative ages (top is youngest; bottom is oldest). This legend is the final project of the geologist, AFTER using attitude symbols to create a cross-section along the above line. The geologist chose to make the cross-section perpendicular to the folds. In this way, he or she ensures that dips (which are measured perpendicular to strike) can be transferred correctly to the cross- section. Note: thrust zones are reverse fault zones.

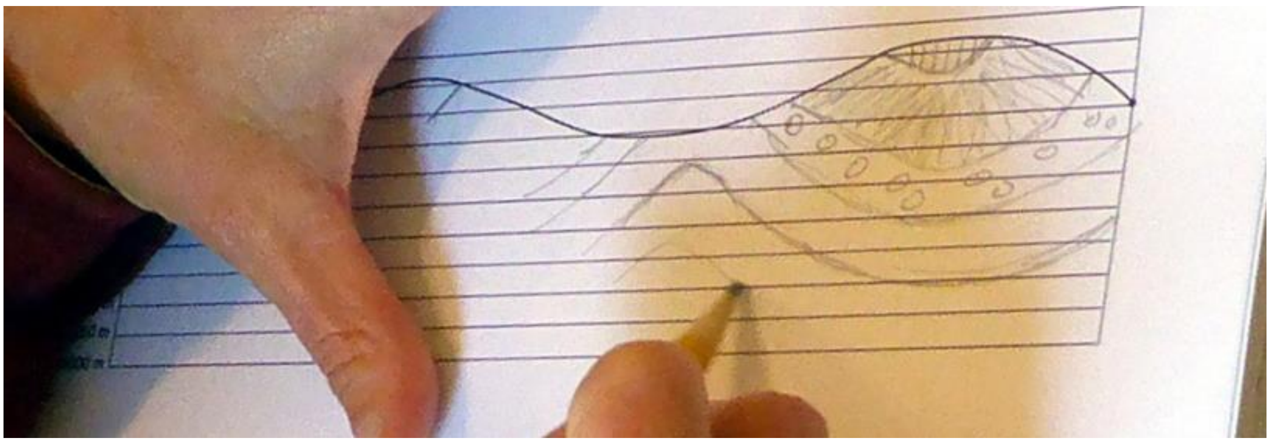
The following instructions explain how geologic cross-sections are made. You will be creating one during lab, so you will need to follow these directions:

Making a structural cross-section

1. Choose carefully where you want to draw the section. To show as much structure as possible, sections are most commonly drawn perpendicular to the general strike of the beds or hinge axes if folds exist. (Example: line X-Y above .)
2. Draw a cross-section line on the geologic map.
3. Make an accurate topographic profile without vertical exaggeration. If your topographic profile is exaggerated, the bed thicknesses and angles in the cross-section won't be correct.
4. Place your profile over the map line, and transfer locations of contacts, and structural features such as fold axes, faults, and unconformities from the map to the profile.
5. On the map, select an attitude symbol that is near the profile line (the closer, the better) and near a contact. Use the dip to extend the contact line a little bit below the surface (use a protractor to be precise). Continue for as many strike/dip symbols as are available along the profile.
   a.) Strike/dip symbols are most valid when they are close to the line. In some parts of the geologic map there are very few strikes and dips: use information farther from the line (extrapolate).
   b.) If the strike is not perpendicular to the profile line, the apparent dip (viewed in the plane of the cross-section) will be less than the actual dip.
6. Choose a bed that appears in multiple places in the profile and sketch it in (lightly, in pencil) both below the surface and projected above the surface, as it may have been before being eroded away. Take account of indicated dips, fold axes, etc. Remember, bed thickness must be the same everywhere. When you have gone as far as you can with the first bed/layer, add others.
7. Be sure to make a logical, physically consistent interpretation. For example, if a formation appears at the surface at one end of the profile and not at the other, you have to explain it away. There are many possibilities: Is it simply not exposed (covered by other strata)? Has it been eroded away (unconformity)? Was it faulted out of the picture? Was it not deposited in that location? You must also be sure that the formations in your structure section stack up according to age. Don't put younger rocks beneath older rocks unless there is a good reason for it.
8. When your lightly penciled sketch looks good, make the lines heavier or ink them. The cross-section can be colored lightly to correspond with the colors on the geologic map. Label formations (Kfu, Tpt, etc.) and add an explanation or legend as on the geologic map, showing what the various colors and symbols stand for. Put a title on the completed cross-section.




3750 m
3500 m
3250 m
3000 m
2750 m
Y



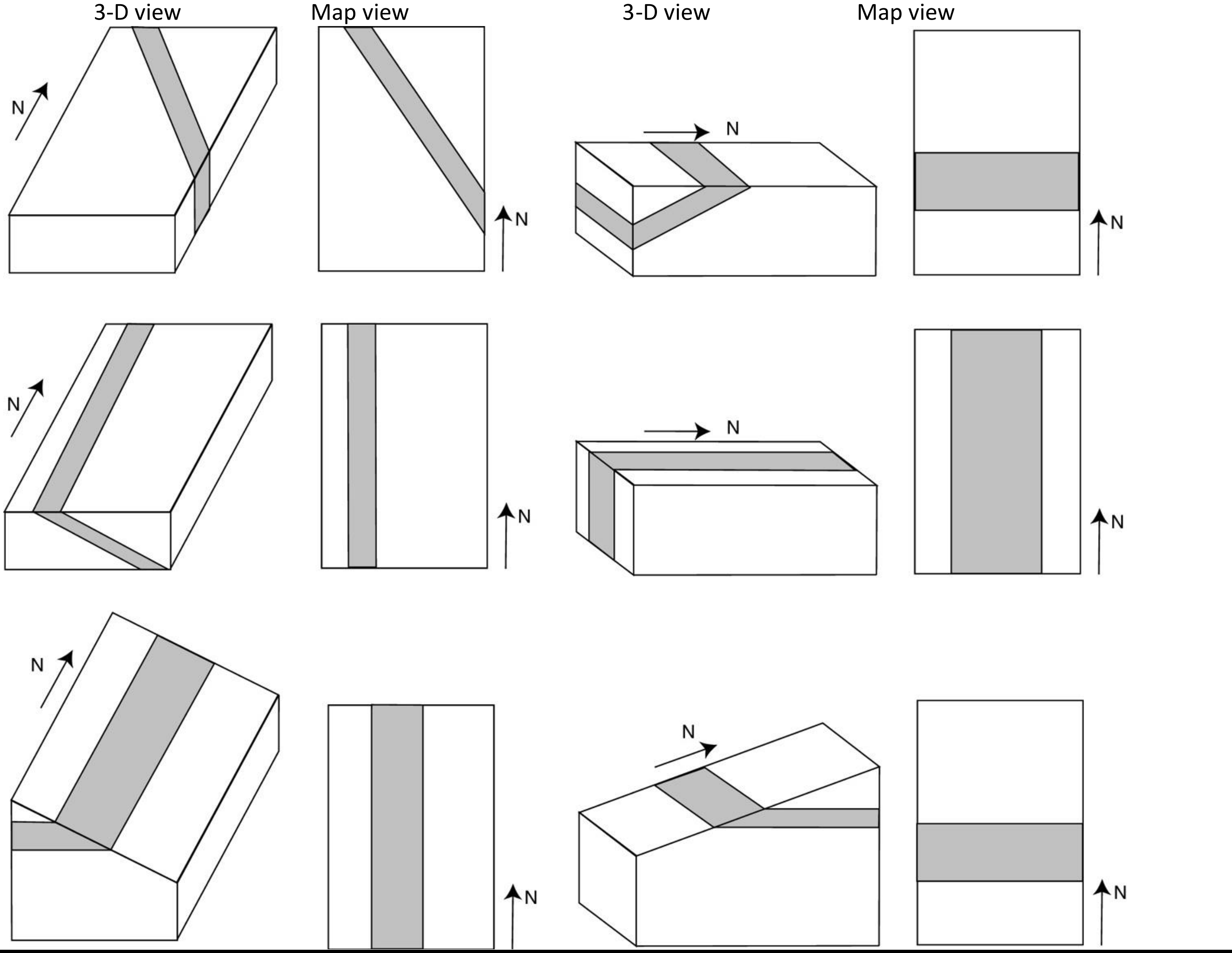
Geologic Mapping and Cross Sections Prereading Homework

For true/false questions below, circle the correct choice:

1.	(True / False) When you make a geologic cross-section, you can start with a topographic profile of any vertical exaggeration (as long as you indicate what the exaggeration is).
2.	(True / False) Use only attitude symbols whose strike is parallel to the cross-section line to ensure true dips.
3.	(True / False) The legend is the final piece to a geologic map, completed after the cross-section.
4.	(True / False) Cross-sections should be done lightly in pencil first, because things might need to be modified later as you add more information.
5.	(True / False) Choose the location of your cross-section profile line, so that it is perpendicular to any fold structures present.
6.	(True / False) If there are no attitude markers near the profile line, you leave the area blank.
7.	(True / False) Beds must maintain uniform thickness throughout the cross-section, unless they pinch out or are eroded elsewhere.
8.	Follow the instructions on the making a geologic cross-section from the previous page and sketch a geologic cross-section across the geologic map of San Francisco shown on the first page of the prereading of this lab. Follow the X-Y cross-section line provided. *(**1:1 nonexaggerated topographic profile should be created BEFORE a geologic cross-section. However, for purposes of this exercise, assume that SF is flat, an acceptable simplification!**)* A geologic cross-section is what you drew last week on every "side" of your box diagrams. Use the strike and dip measurements on the map view to show what the beds do underground, just like you did ast week. X--Y
9.	**Stratigraphy** = vertical sequence of rocks and major geologic events in order from oldest at bottom to youngest at top. Find the stratigraphy associated with the geologic map of San Francisco in the prereading (map you used above – first page of prereading – look at left edge where the rock units are listed by color) and list below, in a vertical column, just the rocks that are part of the cross-section above. Youngest at top. Oldest at bottom.

10. These diagrams show sedimentary beds at different angles – in block diagram and in map view. Some of the block diagrams have flat tops. Others have inclined tops. Measure and place an accurate attitude marker on the map views of each pair. Be careful – don't confuse slope of the hillside with the dip of the bed. Remember, attitude marks go INSIDE bed on map view.

3-D view Map view 3-D view Map view



Geologic Mapping and Cross Sections Lab Exercises

Rockville Geology

Use the attached topographic map of fictitious Rockville and the following tables to create a geologic map atop a topographic map.

STEP 1: Everywhere there is a number on the map, you are looking at a rock outcrop for which you, as the geologist making this map, need to measure bedding orientation or attitude. Stations are set up in the lab (or by video/photo on website) that correspond to these rock outcrops. Go first to these resources and review the rocks and the way they are oriented (dips and strikes of how they come out of the ground). Use protractors to measure and record strike and dip for each station. Enter answers into table below

CHECK ANSWERS WITH INSTRUCTOR FOR CORRECTNESS BEFORE MOVING ON!

STEP 2: Transfer the station values to the map as attitude symbols. *(NOTE: There is already one attitude mark on the map, for the fault.)*

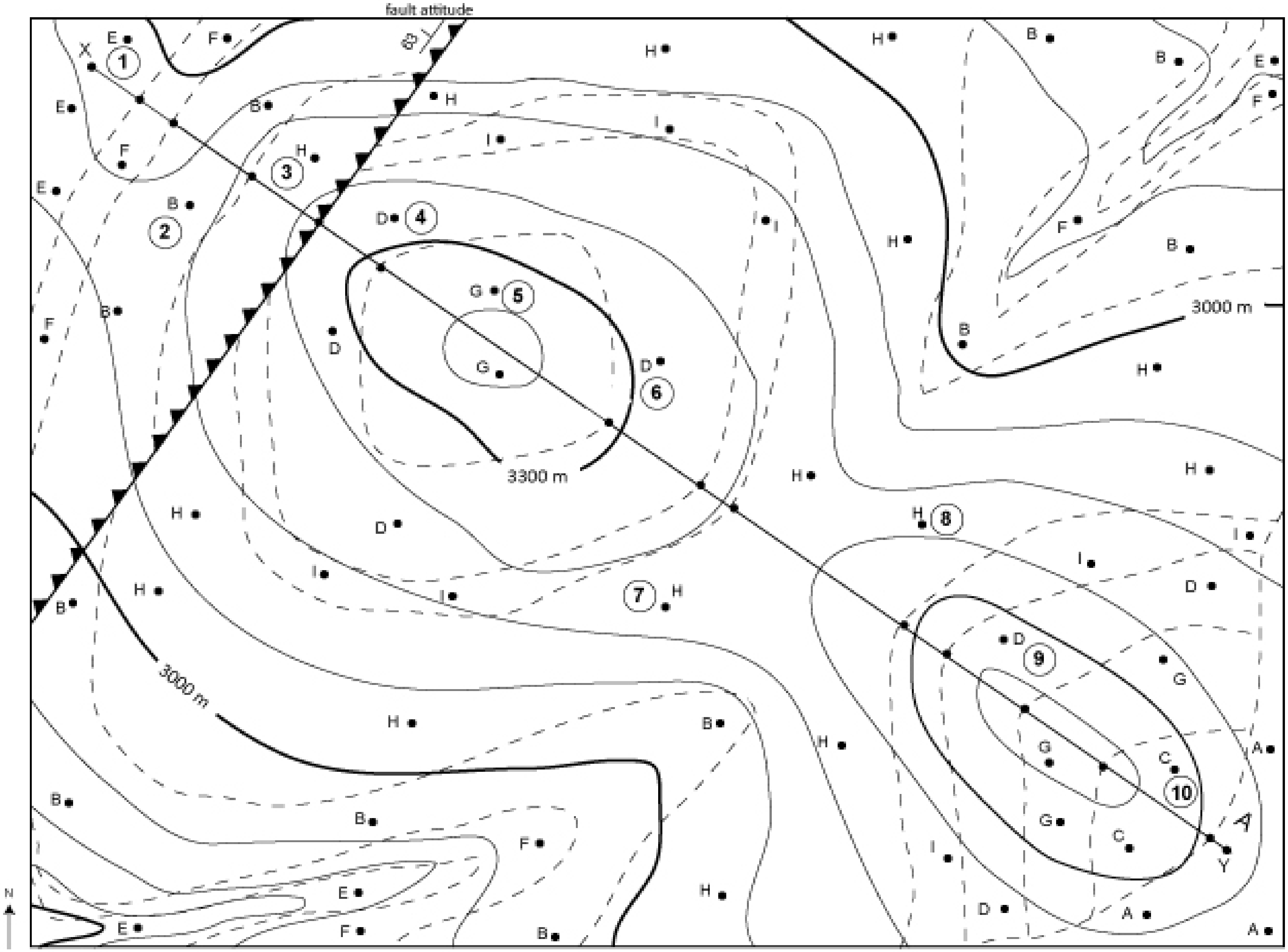
CHECK ANSWERS WITH INSTRUCTOR FOR CORRECTNESS BEFORE MOVING ON!

STEP 3: Everywhere on the map that you see a letter, a geologist found an outcrop of that particular rock. Dashed lines (dashed because they are approximations) outline areas of the same rock formations (thereby creating approximate contacts between beds). Lightly color in rock formations (different color for each formation).

Station #	Rock symbol	Strike and dip	Station #	Rock symbol	Strike and dip
1	E		6	D	
2	B		7	H	
3	H		8	H	
4	D		9	D	
5	G		10	C	

Rock symbol	Formation name and description	Rock symbol	Formation name and description
A	Granite Pegmatite (igneous)	F	Limestone (sedimentary)
B	Sandstone (sedimentary)	G	Conglomerate (sedimentary)
C	Sandstone (sedimentary)	H	Sandstone (sedimentary)
D	Shale (sedimentary)	I	Limestone (sedimentary)
E	Shale (sedimentary)		

Note: No ages are known for these rocks. Order above is random. You will have to use evidence in the map and on the cross-section to determine relative dating. Almost all the rocks are sedimentary, so they would have originally been deposited as flat layers that later were tilted, folded, and/or faulted. **However, note that rock A is a granite pegmatite, which is an igneous rock. See below for how to represent that on your cross-section.**



Rockville QUAD

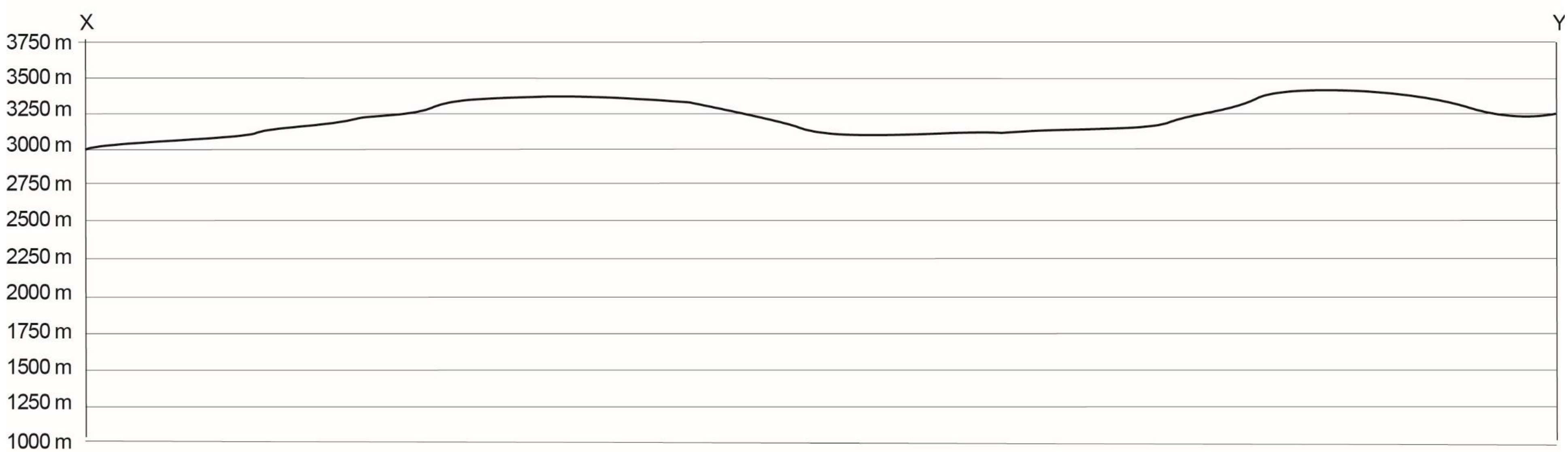
Contour Interval = 75 m

(dashed lines represent bedding contacts -- dashed only to distinguish them from contours; these should all be solid.)

1 km

STEP 3: Create a geologic cross-section along line X-Y. Use the no-exaggeration profile provided here.

- Transfer bed contacts to profile. Use pencil first.
- Remember to keep consistent stratigraphy (order of beds) and thicknesses. Rock units can't cross through each other! For example, if X is between Y and Z in one part of cross-section it should be between Y and Z in all parts.
- Unit A should appear on the right of your cross-section. If your cross-section didn't fit perfectly, it's a printing error. Just be sure you extend it right to include A! A is a granite. **Granites** form deep under volcanoes, where magmas can cool slowly underground. Magmas are buoyant and rise through cracks in the crust. Cracks expand as magmas move through them. Eventually the magmas stop and accumulate, growing into a large magma chamber, shaped like an upside down rain drop. Within these chambers they can slowly cool to form crystalline rocks such as granite. Because granites are not deposited, they have no strike and dip; they intrude from below and cut across all rocks. (Look at figures in Igneous Rocks Lab for examples of what this looks like.) Do your best with shape. Dash it because you're making it up.
- Add color at the last.
- Be sure to label faults (with arrows and names).
- Name all folds (completely) and draw hinge axes (map view and cross-section: characterize hinge axes tilts if exist).



STEP 4: Stratigraphy

When your cross-section is complete, order events and rocks from youngest (top) to oldest (bottom). Include the folding and faulting in your ordered events.

Rock symbol or Event (Fold/Fault)

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	Self-Assessment of Mastery Level	Action plan for improvement
Generate a geologic map based on rock outcrop patterns.	A | B | C | D | F	
Measure, describe, and draw on a geologic map the strike and dip for rock layers that are exposed at Earth's surface.	A | B | C | D | F	
Generate a geologic cross-sections showing subsurface geology based on surface strike and dip data.	A | B | C | D | F	
Evaluate the relative ages and timing of geologic events happening the geologic past in an area, based on a geologic cross-section.	A | B | C | D | F	

INSIGHTS

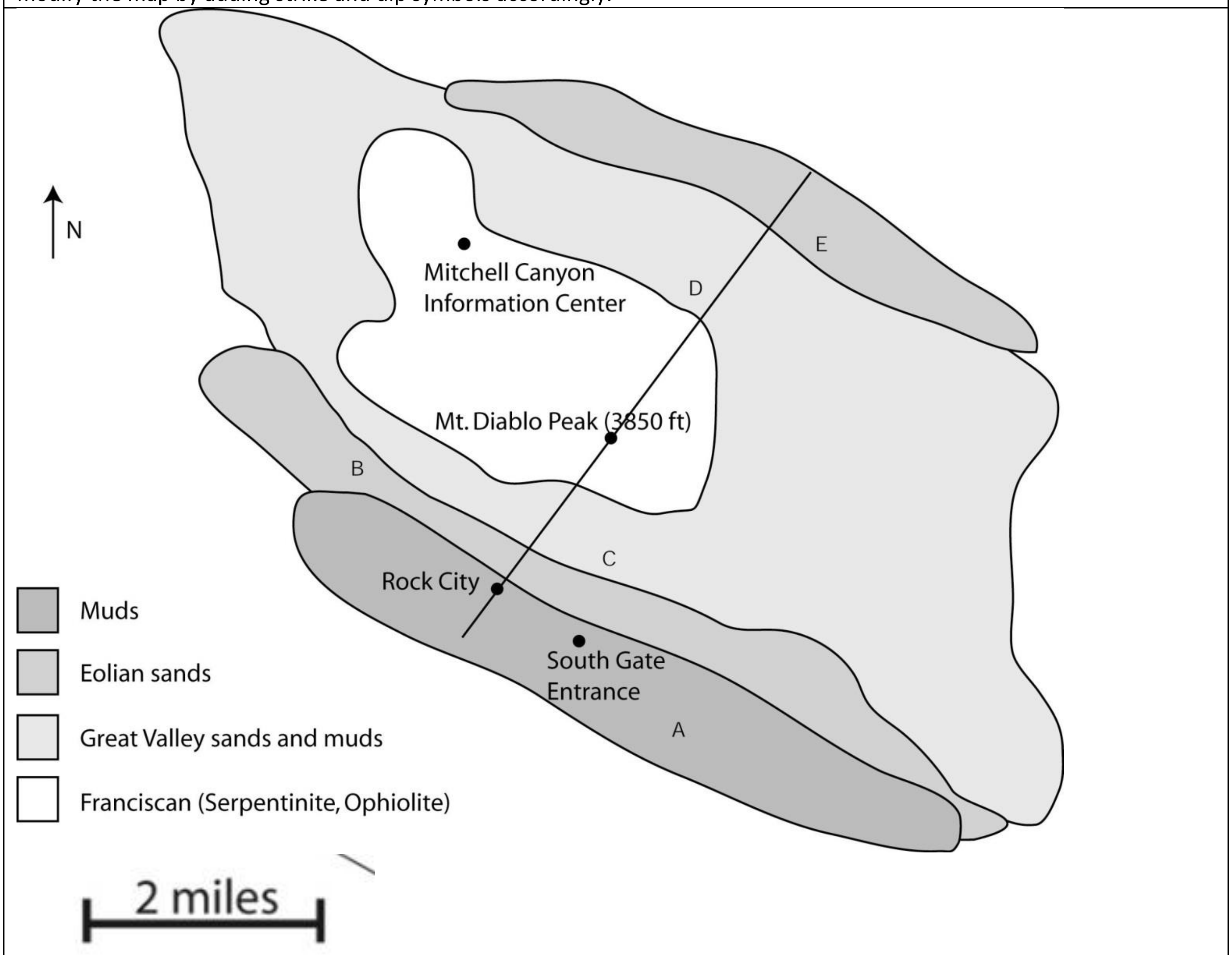
What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Geologic Mapping and Cross Sections Practice Sheet

Remember – the exam questions come directly from the labs, so to do well on the exam, be sure to study ALL the questions on the labs and be able to correctly answer them on the exam. To assist, this study sheet gives you a chance to practice SOME of the skills from recent labs. BE CAREFUL – just because a question appears on this sheet doesn't mean it will show up on the exam and just because a questions doesn't appear on this Practice Sheet doesn't mean that it won't show up on the exam. To be sure you're thoroughly prepared, study all questions from recent labs. Just like on the exam, **show ALL work.** (You may use a calculator.)

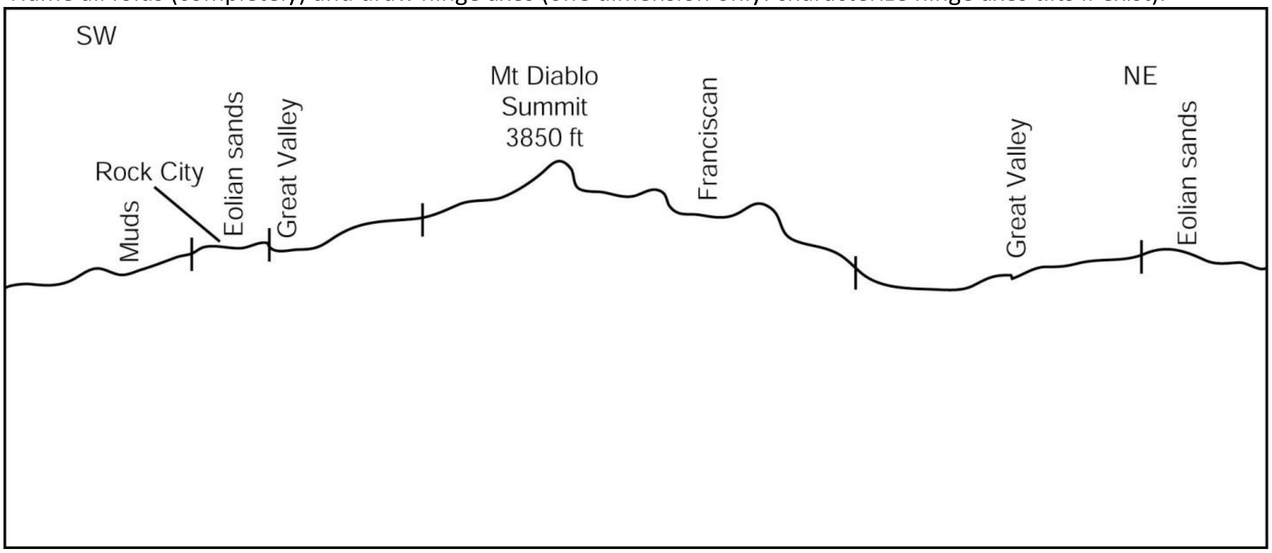
Mt. Diablo Geology

Everywhere there is a letter on the map, you need to measure bedding attitude. Since you can't measure set-up stations at home, be sure you come to the lab to practice measuring them. Meanwhile, use the values given in the table below to modify the map by adding strike and dip symbols accordingly.



Station #	Rock symbol	Strike and dip	Station #	Rock symbol	Strike and dip
A	Muds	N65W 75SW	D	Great Valley sands & muds	N62W 90
B	Aeolian sands	N68W 80SW	E	Muds	N58W 85NE
C	Great Valley sands & muds	N60W 82SW			

Create a geologic cross-section along a line that cuts through Mt. Diablo and intersects the Summit and Rock City. Use the no-exaggeration profile provided here (with bedding contacts already drawn in).
Name all folds (completely) and draw hinge axes (one dimension only: characterize hinge axes tilts if exist).

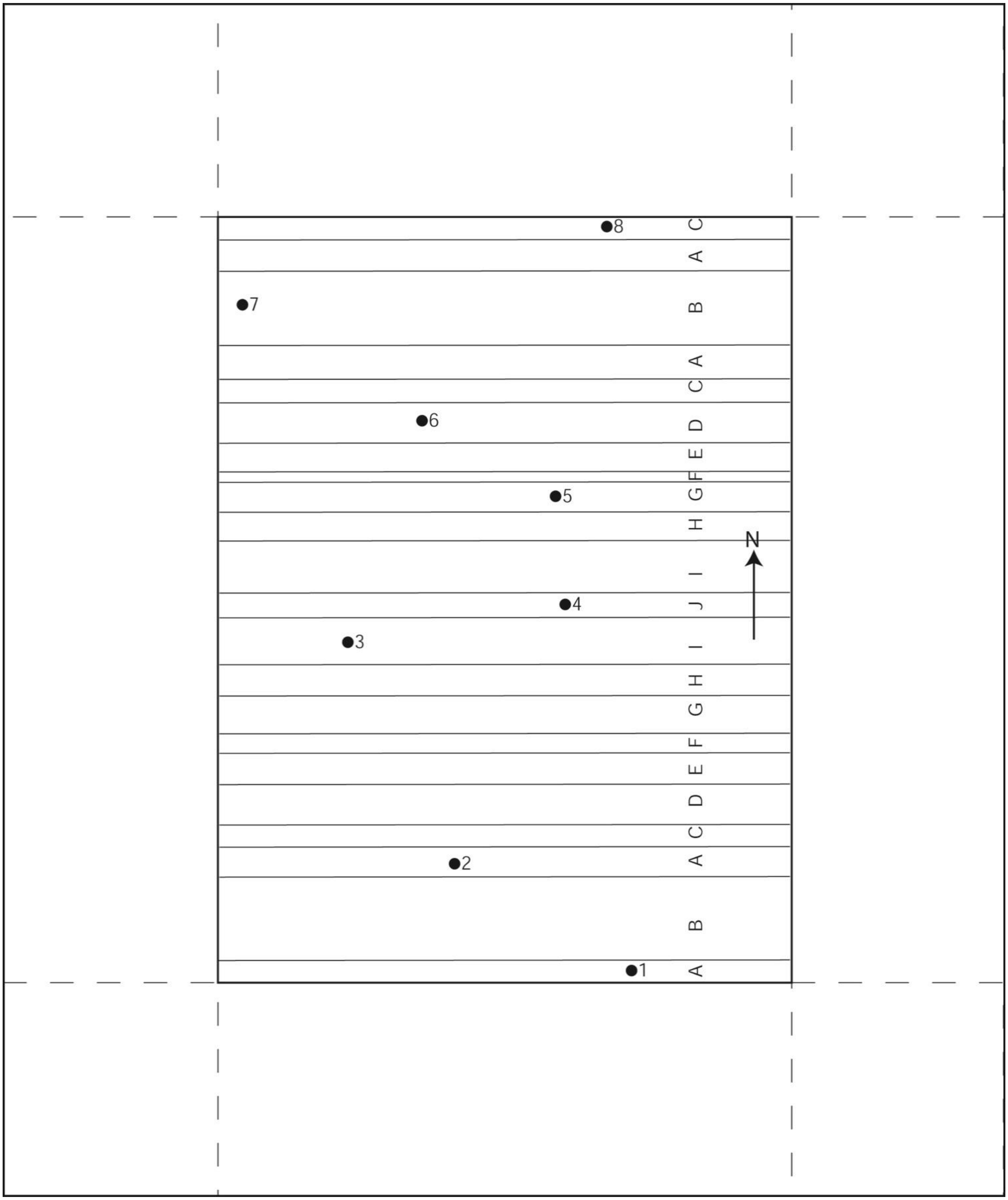


Stratigraphy When your cross-section is complete, order events and rocks from youngest (top) to oldest (bottom). Include the folding and faulting in your ordered events.

Rock symbol or Event (Fold/Fault)

Add attitude markers to diagram (based on data in table below).
Complete all blank sides on the box diagram.
Label all layers in increasing age (1=youngest).
Where folds exist, identify structure. Draw in the axial plane, appropriate fold arrows relative to hinge axis, plunge symbols, and plunge values (if appropriate).

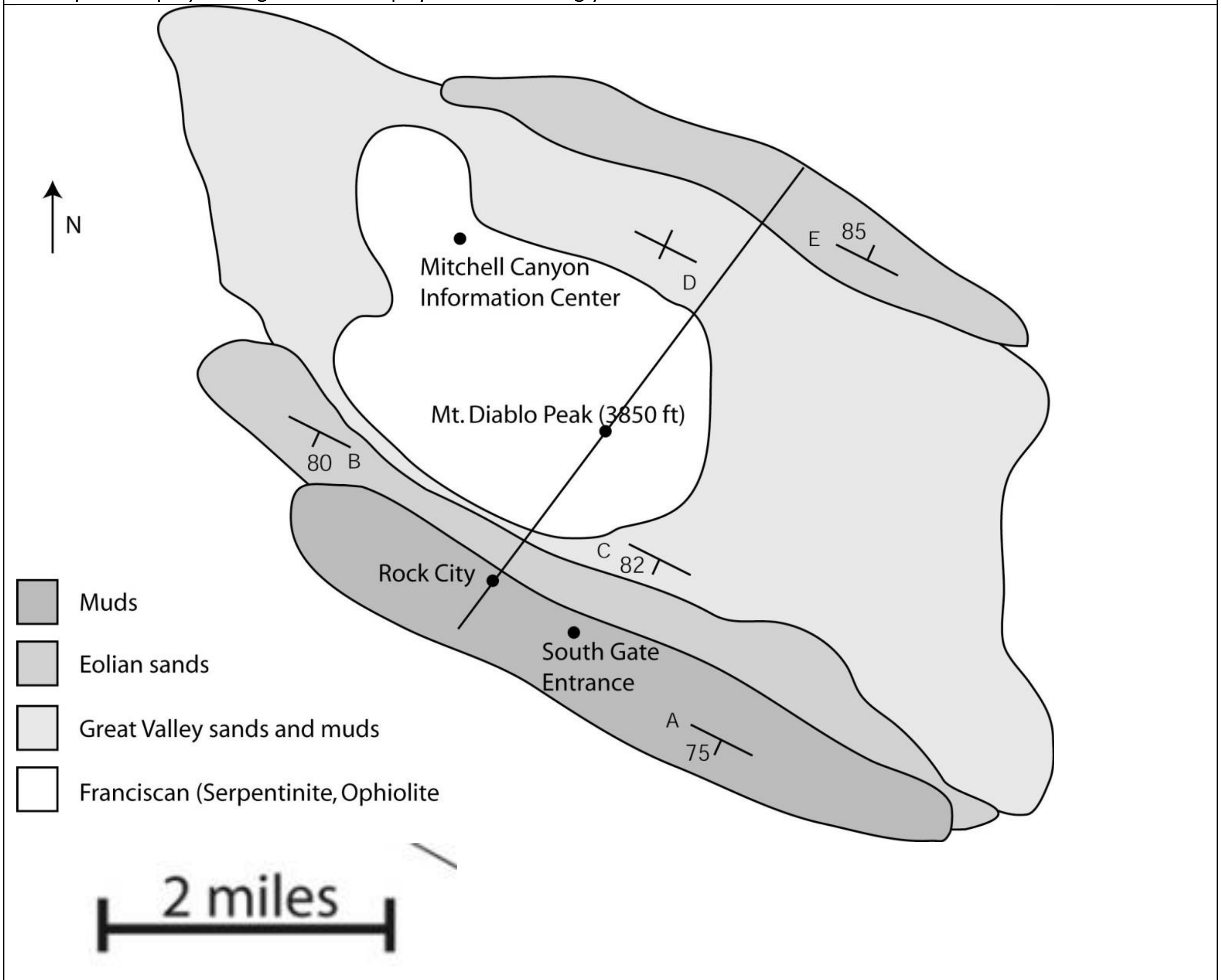
Station #	Rock symbol	Strike and dip	Station #	Rock symbol	Strike and dip
1	A	N90W ~35S	5	G	N90W ~45S
2	A	N90W ~45N	6	D	N90W ~55S
3	I	N90W ~30N	7	B	N90W horizontal
4	J	N90W horizontal	8	C	N90W ~35N


N
8
7
6
5
4
3
2
1
C
A
B
A
C
D
E
F
G
H
I
J
I
H
G
F
E
D
C
A
B
A

KEY

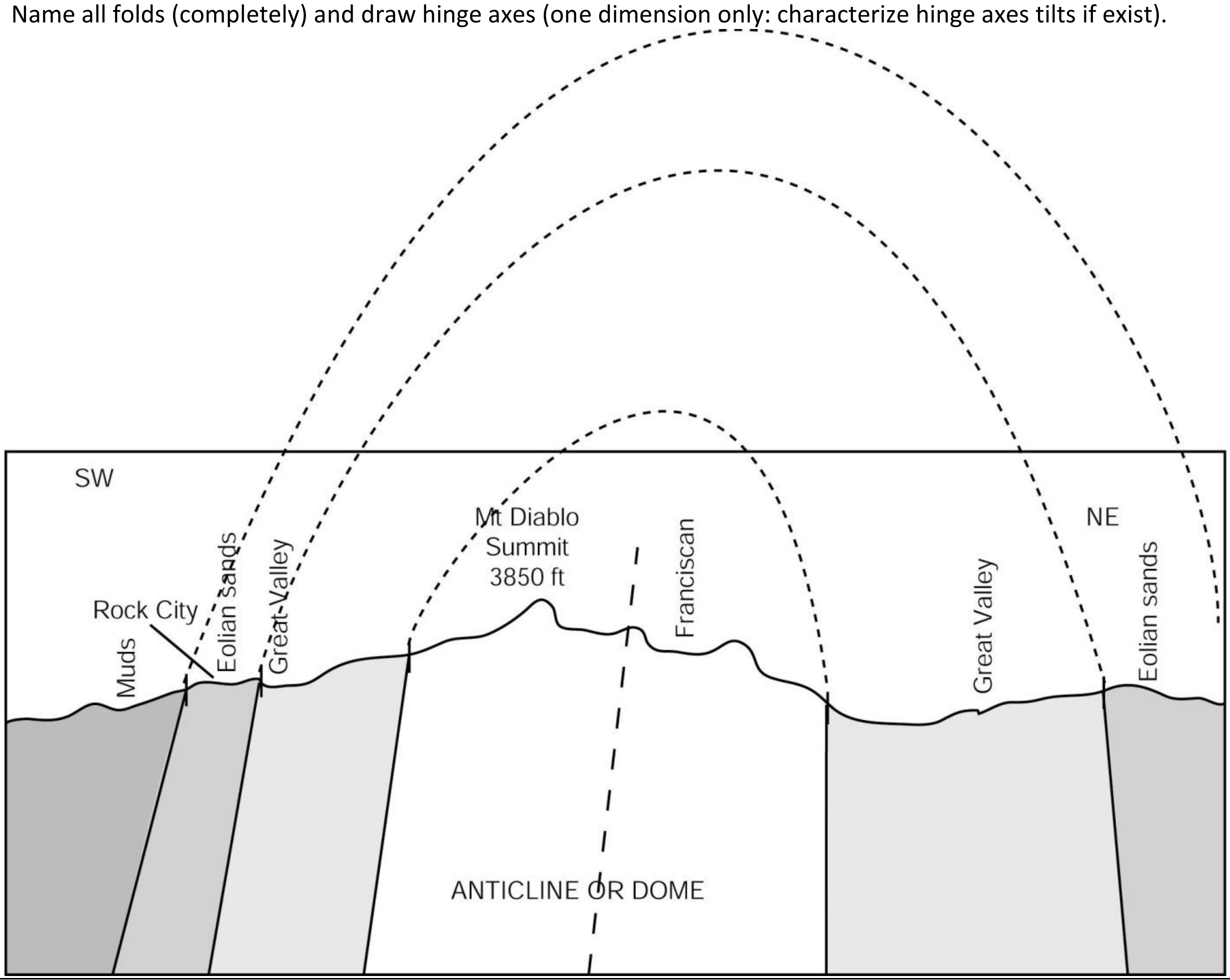
Mt. Diablo Geology

Everywhere there is a letter on the map, you need to measure bedding attitude. Since you can't measure set-up stations at home, be sure you come to the lab to practice measuring them. Meanwhile, use the values given in the table below to modify the map by adding strike and dip symbols accordingly.



Station #	Rock symbol	Strike and dip	Station #	Rock symbol	Strike and dip
A	Muds	N65W 75SW	D	Great Valley sands & muds	N62W 90
B	Aeolian sands	N68W 80SW	E	Muds	N58W 85NE
C	Great Valley sands & muds	N60W 82SW			

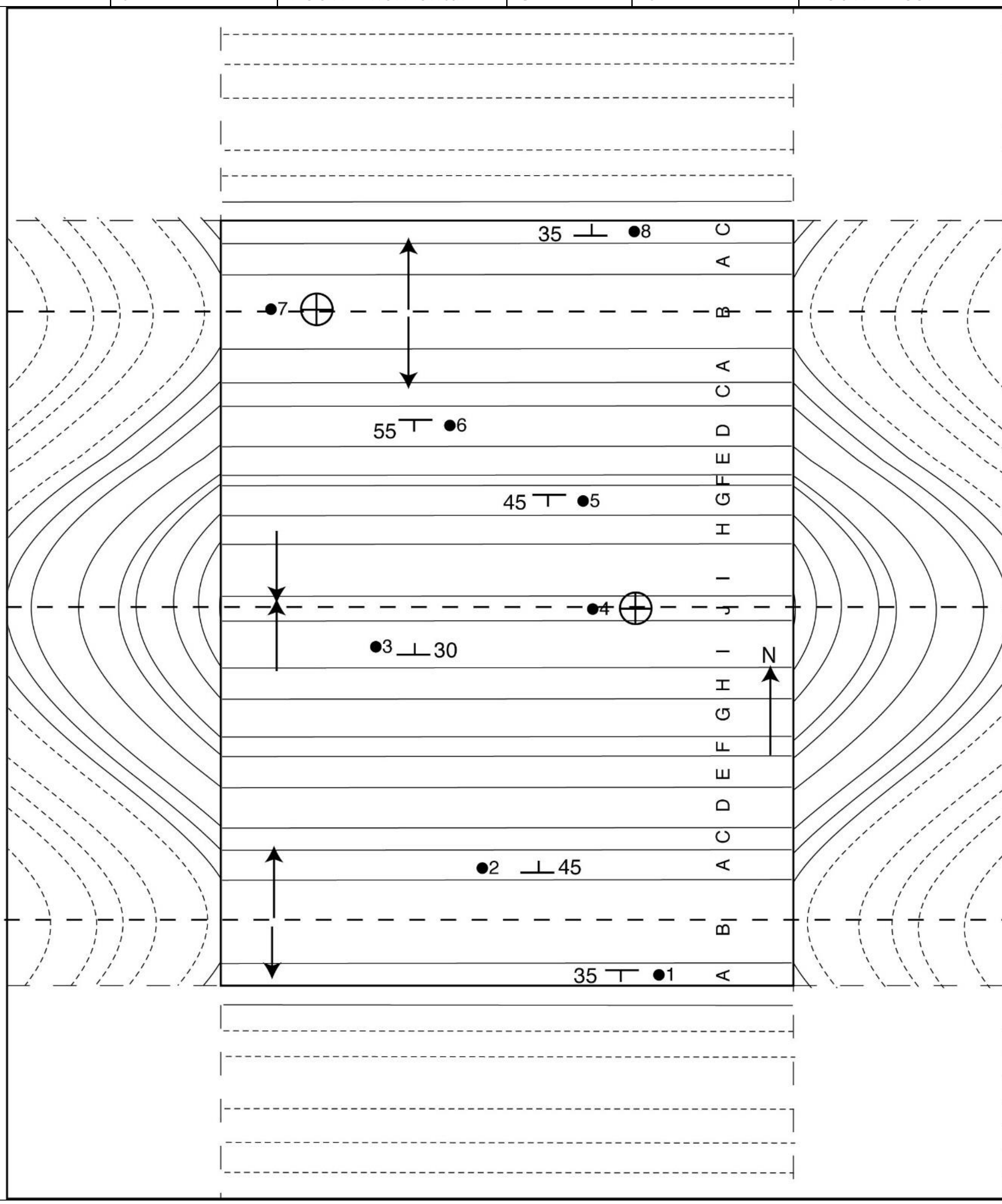
Create a geologic cross-section along a line that cuts through Mt. Diablo and intersects the Summit and Rock City. Use the no-exaggeration profile provided here (with bedding contacts already drawn in).
Name all folds (completely) and draw hinge axes (one dimension only: characterize hinge axes tilts if exist).



Stratigraphy When your cross-section is complete, order events and rocks from youngest (top) to oldest (bottom). Include the folding and faulting in your ordered events.

Rock symbol or Event (Fold/Fault)
Dome/Anticline fold
Muds
Aeolian Sands
Great Valley sands and muds
Franciscan (Serpentinite, Ophiolite)

Add attitude markers to diagram (based on data in table below). Complete all blank sides on the box diagram. Label all layers in increasing age (1=youngest). Where folds exist, identify structure. Draw in the axial plane, appropriate fold arrows relative to hinge axis, plunge symbols, and plunge values (if appropriate).					
Station #	Rock symbol	Strike and dip	Station #	Rock symbol	Strike and dip
1	A	N90W ~35S	5	G	N90W ~45S
2	A	N90W ~45N	6	D	N90W ~55S
3	I	N90W ~30N	7	B	N90W horizontal
4	J	N90W horizontal	8	C	N90W ~35N

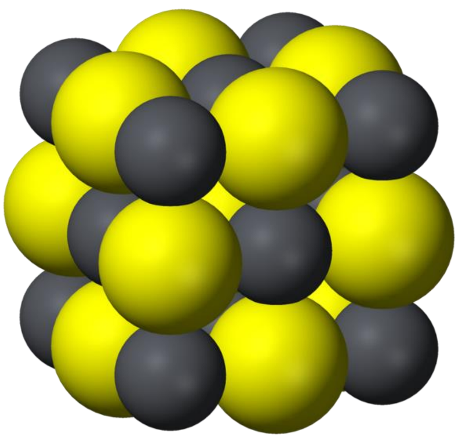


Minerals

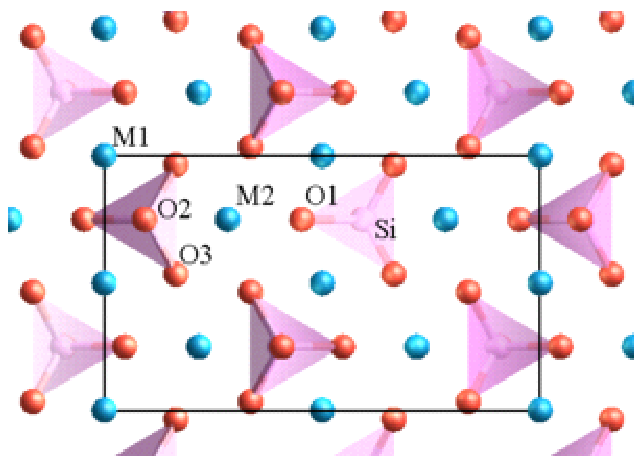
A **mineral** is a naturally occurring, inorganic solid with a characteristic chemical composition, distinctive physical properties, and a definite internal atomic arrangement (crystal structure). A **rock** is an aggregation of crystals or grains of one or more minerals. Examples:

- **Granite** is an **igneous rock** that contains these minerals: Quartz, Micas (Biotite or Muscovite), and Potassium Feldspar
- Liquid mercury (Hg), or **quicksilver**, is NOT a mineral. It becomes a mineral when it freezes at -40°C.
- **Sugar** ($C_6H_{12}O_6$) is organic (contains C, H, and O), so sugar is NOT a mineral.
- Salt (NaCl) is inorganic. Salt is a mineral called **Halite**.
- **Glass** (Si + O, not bonded in a crystalline structure) is NOT a mineral.

Minerals have chemical formulas, which indicate the relative proportions of atoms that make up the mineral. These atoms bond to each other in a specific geometric arrangement (making them **crystalline**). For example, *Galena* – PbS – has equal amounts of Lead (Pb) and Sulfur (S) atoms. The way that these atoms bond and arrange themselves determines the shape of the crystals that form. Some minerals can have multiple atoms substituting for one or more of the atom sites. These mineral formulas indicate a range. For example, *Olivine* – $(Mg,Fe)_2SiO_4$ – has 7 types of atom sites; 1 of every 7 is held by Silicon (Si), 4 by Oxygen (O), and 2 by either Magnesium (Mg) or Iron (Fe). The amount of Mg or Fe can vary, which does change the shape and color of the mineral to some extent, but leaves it still as the Olivine mineral



Crystalline shape and atomic bonding of Galena, PbS.
Image: Ben Mills – Public Domain.



Underlying crystalline shape and atomic bonding of olivine.
Image: Matanya – Public Domain.

WHAT PHYSICAL PROPERTIES HELP US IDENTIFY MINERALS?

CRYSTAL SHAPE OR HABIT

If a crystal grows without obstruction, it can develop flat edges called crystal faces, which reflect the internal crystal structure. Most minerals do not display perfect crystal shape, because they did not have enough space to grow. (Crystals are common in caves and rock cavities.) Examples:

- PRISM (6-sided): Quartz – coming to a point; Gypsum no point.
- RHOMBOHEDRON: Calcite
- BLADES: Kyanite
- CUBIC: Halite
- OCTAHEDRON (eight-sided polygon) or CUBIC: Galena, Fluorite
- TABULAR (like a tablet of stone or paper): Talc, MICAS: Biotite or Muscovite
- DODECAHEDRON (12-sided polygon): Garnet
- NEEDLES: Actinolite

HARDNESS

Hardness is a mineral's ability to resist scratching. Moh's hardness scale consists of 10 minerals arranged in order of increasing hardness from 1 (softest) to 10 (hardest). Hardness is a relative property, not absolute. If mineral A scratches mineral B, then the scratched mineral (B) is softer.

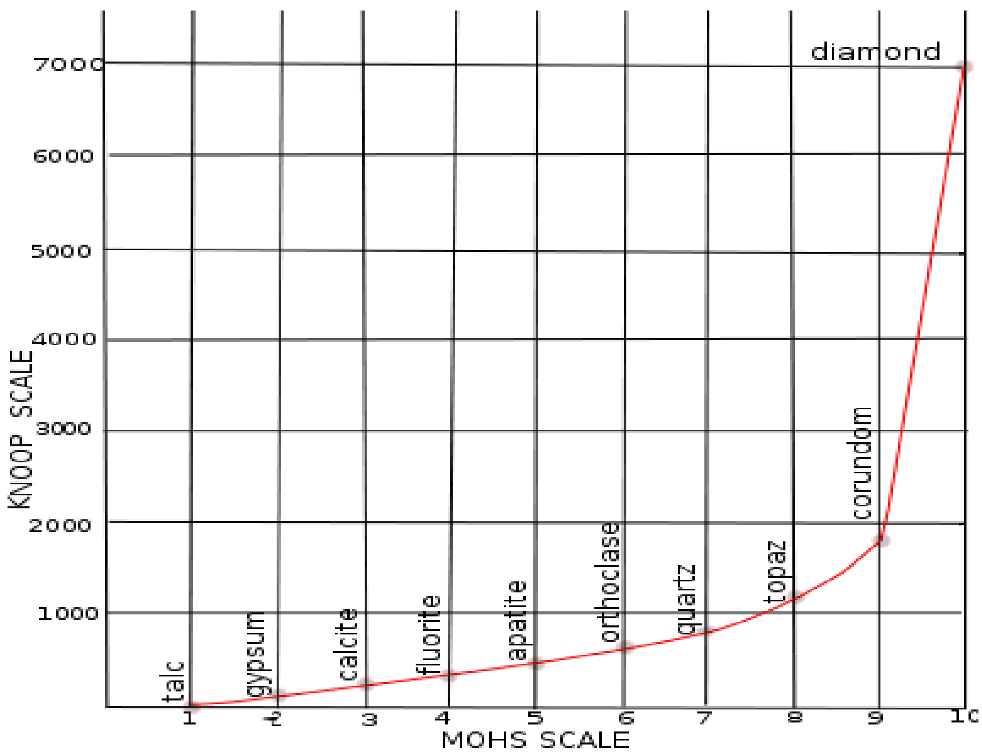
Moh's scale:

1. Talc
2. Gypsum
3. Calcite
4. Fluorite
5. Apatite
6. Orthoclase
7. Quartz
8. Topaz
9. Corundum
10. Diamond

Other items:

2.5 fingernail or copper, including pennies *(post 1900 pennies)*
3.5 brass
4.5 iron wire or nail
5.5 glass or masonry nail or knife blade
6.5 streak plate

When we plot Mohs scale hardness numbers against those on the more quantitative Knoop scale (based on the force needed to make indentations using a diamond), you can see that the change in actual hardness between 1 and 2 and 8 and 9, for example, are not the same. The Mohs scale is relatively stable until it reaches 8, but it jumps exponentially from 9 to 10 (Diamond). *(It is difficult to measure the hardness of diamond, because diamond must be used to measure its own hardness.)*



Knoop Hardness Scale comparison with the Mohs Scale. The Knoop Hardness Scale values are measured as pressures. Unit: g/mm^2. Image: Eurico Zimbres – Creative Commons – CC BY-SA 2.5

Examples of common minerals with unique hardnesses:

- Soft enough to scratch with a fingernail: Talc (1) and Graphite (1) and Gypsum (2),
- Softer than an iron wire or nail, but harder than a copper penny: Calcite (3) and Fluorite (4)
- Softer than glass, but harder than an iron wire or nail: Apatite (5)
- Softer than streak plate, but harder than glass: Potassium Feldspar (6)
- Harder than a streak plate: Quartz (7), Topaz (8), Corundum (9), Diamond (10)

COLOR

Color is often the least useful diagnostic tool, as many minerals appear in a large range of colors. There are a few minerals, however, that are associated with one particular color. Color clarity is defined as **transparent** (clear like window glass), **translucent** (foggy, like looking through sanded glass), or **opaque** (doesn't transmit light – like metals). **Streak** is the color of the mineral when ground to a powder. You determine streak by scratching the mineral across a streak plate and viewing the powdered material left behind. Streak is a much better diagnostic tool than color, as streak does not usually vary for a mineral.

Examples:

Common mineral that is **green**: Olivine

Common minerals that can be **red:**

- Garnet (usually red, but can also be brown or green)
- Hematite (earthy red and metallic grey, but always has a red streak)

Common mineral that can be **pink**: Potassium (K) Feldspar (can also be white)

Common mineral that is **blue**: Kyanite

Common minerals that can appear in **many colors**:

- Quartz (usually colorless, white, or gray, can be any color)
- Calcite (colorless, white, or yellow, can be green, brown, blue, or pink)
- Fluorite (colorless, purple, blue, grey, green, or yellow)

LUSTER

Luster is the appearance (quality and intensity) of light reflected from a mineral surface. Minerals are separated into two categories: those with metallic luster and those without. We can further classify luster as silky, resinous, glassy, greasy, pearly, dull, and earthy. Examples:

- METALLIC: Galena, Pyrite
- GLASSY (or vitreous): Quartz, Calcite, Pyroxene, Hornblende, Garnet, Epidote, Olivine, Actinolite
- DULL: Graphite (sometimes)
- GREASY: Graphite
- ADAMANTINE (brilliant and glassy, like diamond): Topaz
- GLASSY to PEARLY: MICA: Muscovite or Biotite
- GREASY to PEARLY: Talc
- SILKY and SATINY: Gypsum
- SILKY, WAXY, and GREASY: Serpentine
- METALLIC and NONMETALLIC (depending on surface you're observing) Hematite

SPECIFIC GRAVITY OR DENSITY

Specific gravity (s.g.) is a measure of how much more dense a material is than an equal volume of water. Water has a density of 1 g/cm^3. Material with s.g. of 2 is twice as dense as an equal volume of water. If X has a s.g. of 2 and Y of 5, then Y is 5/2 or 2.5 times heavier than X. You can use this information to determine masses of equal volumes of A and Y. Most common minerals have specific gravities between 2.3 and 3.8. Minerals much more dense that these values can be readily identified by their heft. Examples:

- 7.6 times heavier than an equal volume of water – Galena
- 5.2 times heavier than an equal volume of water – Magnetite
- 5 times heavier than an equal volume of water – Pyrite

OTHER DIAGNOSTIC PROPERTIES

Some minerals have special characteristics that make them easy to identify. Examples:

- Potassium Feldspar has **exsolution lamellae** – thin inclusions of white Feldspar within pink Feldspar.
- Halite tastes salty.
- Magnetite is magnetic.
- Calcite displays double refraction (two images) and reacts (bubbles) with acid.
- Plagioclase Feldspar has twinning (parallel grooves – like record grooves).

CLEAVAGE & FRACTURE

Cleavage describes the tendency of a mineral to break along flat surfaces (planes). These surfaces correspond to planes of weak bonds in the mineral's crystal structure. For example, micas are sheet silicates, which means they are made up primarily of strong sheets of silicon and oxygen atoms. These individual sheets are bonded to each other through weak bonds made with atoms like Fe, Mg, Ca, etc. When micas are hit, they break most easily between sheets.

We describe cleavage by the number of unique cleavage planes (parallel planes are not unique) and the angle between those planes. Since micas cleave in sheets, they exhibit one direction of cleavage (no angle measurement between different cleavage surfaces, because there's only one surface). *Note: Sometimes it is difficult to tell the difference between cleavage faces and crystal faces. Look at the edges of the surface to see if it looks broken or if it looks like it grew that way. Broken surfaces tend to have a step-like look on their corners or edges. Crystal faces are more regular and smooth. Note: in many cases cleavage planes are the same planes as crystal faces.*

Fracture is a description of how a rock breaks when it doesn't cleave along a plane. Most fractures are irregular and nondiagnostic, but some, like conchoidal, even, and splintery fracture can be helpful in identifying minerals. Olivine, garnet, and quartz are well known for their conchoidal fracture (which is the typical fracture pattern you see when you break nontempered glass – a clamshell-like appearance).

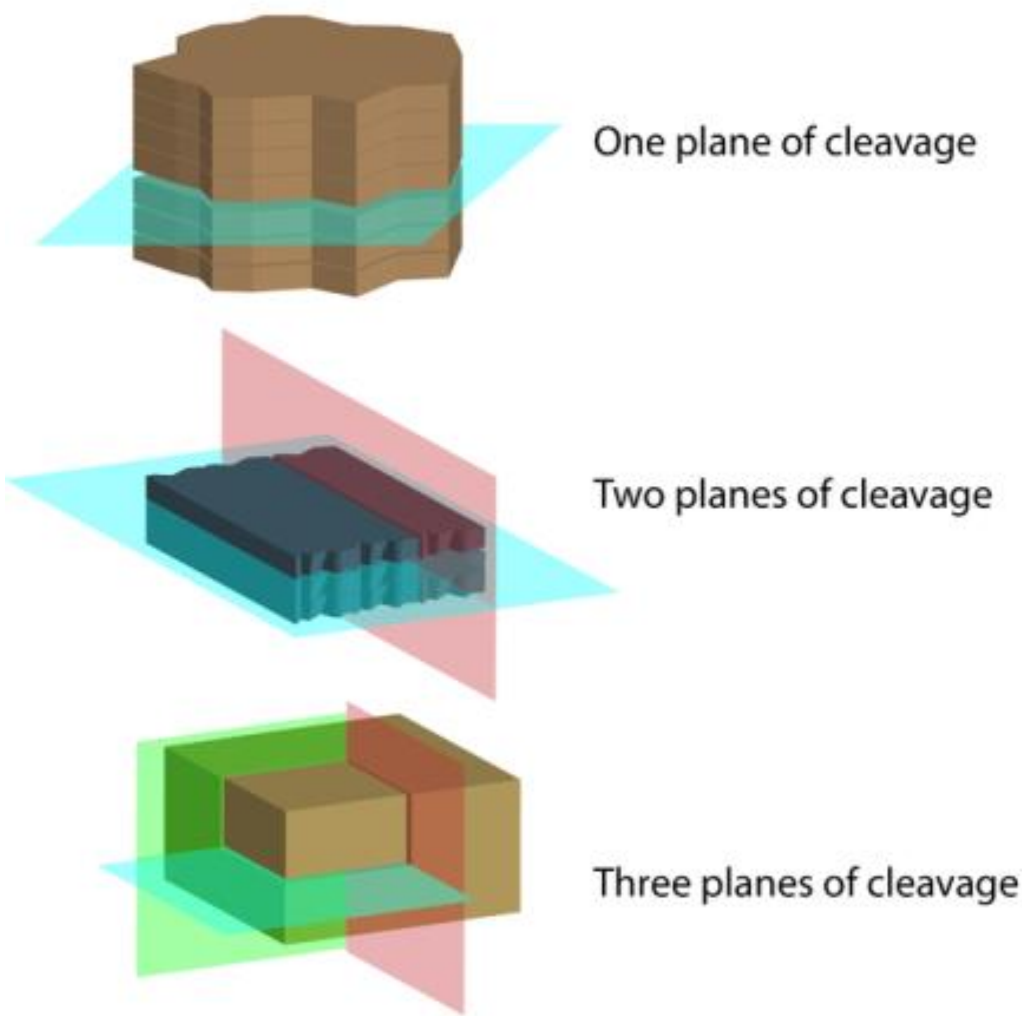


Image: Jillcurie – Creative Commons – CC BY-SA 3.0

Examples:

- One direction of cleavage, perfect (sheets) Irregular fracture on other sides: Muscovite or Biotite
- Two directions of cleavage at 90°and irregular fracture on other surfaces: Feldspars
- Three directions of cleavage, not at 90°: Calcite
- Three directions of cleavage at 90° (cubes): Halite, Galena
- 4 directions of cleavage, greater than 90°: Fluorite
- Conchoidal fracture (no cleavage): Quartz
- Splintery fracture: Hornblende
- Uneven or irregular fracture: most real samples!

Mineral types

Although there are 1000s of minerals known on Earth's surface (and new ones being discovered yearly), only a few are considered common rock-forming minerals. Only a few elements make up the majority (99%) of Earth's crust. The minerals made up of these elements, therefore, are the most commonly found. Since Oxygen and Silicon represent over 75% of the Earth's crust (by weight), the minerals made up of Silicon and Oxygen are the most abundant. These minerals are called Silicates. Their basic molecular building block is the Silicon-Oxygen tetrahedron, a molecule that consists of one Silicon atom surrounded by four Oxygens, in the shape of a tetrahedron. These tetrahedron connect to each other and other elements, like Fe and Mg, to create a range of different silicate minerals – all with crystal shapes that reflect their underlying molecular structure. The most abundant elements in Earth's crust (in decreasing weight percent abundance) are Oxygen (O) 47%; Silicon (Si) 28%; Aluminum (Al) 8%; Iron (Fe) 5%; Calcium (Ca) 3.6%; Sodium (Na) 2.8%; Potassium (K) 2.6%; Magnesium (Mg) 2.1%.

Mineral Groups and Chemical Formulas (Summary)

Silicates

Amphibole family:

- Hornblende $(Ca,Na)_{2\text{-}3}(Fe,Mg,Al)_5Si_6(Si,Al)_2O_{22}(OH)_2$
- Actinolite $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$

Chlorite $(Mg,Fe)_5(Al,Fe)_2Si_3O_{10}(OH)_8$

Epidote $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$

Feldspar family:

- Plagioclase Feldspars: $CaAl_2Si_2O_8$ to $NaAlSi_3O_8$
- Potassium Feldspars: $KAlSi_3O_8$

Garnet $X_3Y_2(SiO_4)_3$ where X and Y are combinations of Ca, Mg, Fe, and Al

Kyanite Al_2SiO_5

Mica family:

- Biotite $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$
- Muscovite $KAl_3Si_3O_{10}(OH)_2$

Olivine $(Mg,Fe)_2SiO_4$

Pyroxene family: *Augite $Ca(Mg,Fe,Al)(Al,Si)O_6$

Quartz SiO_2

Serpentine $Mg_6Si_4O_{10}(OH)_8$

Talc $Mg_3Si_4O_{10}(OH)_2$

Carbonates

Calcite $CaCO_3$

Sulfates

Gypsum $CaSO_4 \cdot 2(H_20)$

Native elements

Graphite C

Sulfides

Galena PbS

Pyrite FeS_2

Halides

Fluorite CaF_2

Halite NaCl

Oxides

Hematite Fe_2O_3

Magnetite Fe_3O_4

Corundum Al_2O_3

Mineral Identification Chart – LAB

METALLIC MINERALS (listed in decreasing hardness) Review mineral formula to connect to family! H=Hardness; SG = specific gravity (density)

Mineral	H	SG	Streak	Color	Form	Cleavage/Fracture	Diagnostic properties
Pyrite FeS_2	6-6.5	5	Dark grey	Brass yellow; tarnishes brown.	Cubes or octahedrons	Brittle. No cleavage.	Cubic form, brassy color, and SG=5.
Magnetite Fe_3O_4	6	5.2	Dark grey	Silvery grey to black. Tarnishes grey. Opaque.	Octahedrons	No cleavage.	Attracted to a magnet. SG=5.2. No cleavage.
Hematite Fe_2O_3	1.5-6	2.1-2.6	Red to red-brown	Silvery grey, black, or brick red. Luster can be nonmetallic.	Thin tabular crystals or shapeless masses.	No cleavage.	Red streak. Metallic + nonmetallic. Earthy red.
Galena PbS	2.5	7.6	Grey to dark grey	Silvery grey. Tarnishes dull grey.	Cubes and octahedrons	Brittle. 3 good cleavage planes at 90° (cubes).	SG=8! Silver cubes (form and cleavage).
Graphite C	1	2.1-2.3	Dark grey	Silvery grey to black.	Flakes, short hexagonal prisms, and masses.	1 excellent cleavage plane.	Dark grey. H=1. Greasy. Dark grey streak.

- Note: All metallic minerals have their metallic luster as one of their diagnostic properties.
- Massive or massive as crystal form means lacking defined form.

NONMETALLIC MINERALS (listed in decreasing hardness) Review mineral formula to connect to family! H=Hardness; SG = specific gravity (density)

Mineral	H	SG	Streak	Color (and/or luster)	Form	Cleavage/Fracture	Diagnostic properties
Corundum Al_2O_3	9	4	White	Gray, blue, pink, brown. Glassy or dull. Translucent to opaque.	Hexagonal prisms with striated, flat ends. Barrel shaped.	No cleavage.	H=9. Barrel-shaped, flat-end hexagons.
Garnet $X_3Y_2(SiO_4)_3$ where X and Y are combinations of Ca, Mg, Fe, Al	7	3.5-4.3	White	Red, black, or brown; can be yellow, green, pink. Glassy. Translucent.	Dodecahedrons (12-sided polygons)	No cleavage. Brittle. Conchoidal fracture.	Dodecahedron form, red (sometimes), glassy, conchoidal fracture, H=7.
Olivine $(Mg,Fe)_2SiO_4$	7	3.3-3.4	White	Pale or dark olive green to yellow-green or brown-green. Glassy. Transparent.	Short prisms (usually too small to see).	Conchoidal fracture. Brittle.	Green, conchoidal fracture, glassy, H=7. Usually granular. Not a hexagonal crystal.
Quartz SiO_2	7	2.7	White	Colorless, white, or gray; can occur in all colors. Glassy and/or greasy.	Massive; or hexagonal prisms that end in a point.	Conchoidal fracture.	Glassy, conchoidal fracture, H=7. Hex. prism with pointed end.
Epidote $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$	6-7	3.3-3.6	White	Green (with yellow or brown tinge). Translucent to opaque. Glassy.	Striated prisms, or massive.	One good, one poor and rarely visible.	H=7. Green. Striated crystal faces. Massive. Usually opaque.

Mineral	H	SG	Streak	Color (and/or luster)	Form	Cleavage/Fracture	Diagnostic properties
Kyanite Al_2SiO_5	4-7	3.6	White	Patchy blue; can be green, white, gray. Glassy, pearly. Translucent.	Bladed masses. Flexible crystals, bent or twisted	One perfect cleavage plane parallel to blades.	Blue, flexible blades.
Amphibole family: **Actinolite** $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	6	3-3.5	White, green	Green (can be white to pink as well). Glassy. Opaque.	Long, thin columnar or needle-like crystals.	2 good planes. Angles: 56° and 124°.	Green, thin needles.
Plagioclase Feldspar family: Anorthite and Labradorite $CaAl_2Si_2O_8$ to Oligoclase and Albite $NaAlSi_3O_8$	6	2.6-2.8	White	Colorless, white, gray, or black; can have iridescent play of color from within. Translucent to opaque.	Tabular crystals or thin needles	2 good cleavage planes at nearly right angles.	Twinning. Iridescent colors (blues and greens). 2 cleavages at 90°. H = 6.
Potassium Feldspar family: Orthoclase and Microcline $KAlSi_3O_8$	6	2.5-2.6	White	Pink. Or white, orange, brown, gray, green. Translucent to opaque.	Octahedrons or decahedrons when in rare perfect form. Normally weathered to tabular form.	2 good cleavage planes at nearly right angles.	Subparallel exsolution lamellae. 2 cleavages at 90°. Pink or white color. H = 6. No twinning.
Pyroxene family: Augite $Ca(Mg,Fe,Al)(Al,Si)O_6$	5.5-6	3.2-3.5	White, pale grey	Green to black; opaque.	Short, 8-sided prisms (if visible).	2 good cleavage planes at nearly right angles.	H=5.5. Dark green or black. 2 cleavages at 90°. (Looks like HB.)
Amphibole family: **Hornblende** $Ca(Mg,Fe)_4Al(Si_7Al)O_{22}(OH)_2$	5.5	3-3.3	Grey-green, white	Dark green to black. Opaque.	Long, perfect prisms.	2 cleavages planes. Angles: 60° and 120°. Brittle. Splintery fracture.	H=5.5. Dark green or black. 2 cleavages at 60° & 120°. Splintery fracture. Long prisms.
Serpentine $Mg_6Si_4O_{10}(OH)_8$	2-5	2.2-2.6	White	Pale or dark green, yellow, grey. Opaque. Dull or silky.	Smooth, rounded masses.	No cleavage.	Mottled green color. Smooth, curved surfaces. No cleavage. H: 2-5. Waxy luster.
Fluorite CaF_2	4	3-3.3	White	Colorless, purple, blue, grey, green, or yellow. Glassy. Opaque to transparent. Rainbow luster in places.	Usually cubes or octahedrons.	4 excellent cleavage directions at angles greater than and less than 90°. Gives crystal shape triangular faces. Brittle.	Cubic or octahedral form. 4 directions of cleavage. Triangular faces. Rainbow luster in places.
Calcite $CaCO_3$	3	2.7	White	Usually colorless, white, or yellow, can be green, brown, or pink. Glassy. Opaque to transparent.	Rhombohedra.	3 excellent cleavage planes at 75 and 105°.	Bubbles in HCL. Double refraction (2 images visible through clear sample). Rhombs, 3 cleavage planes (not 90°), H=3.

Mineral	H	SG	Streak	Color (and/or luster)	Form	Cleavage/Fracture	Diagnostic properties
Mica family: **Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	2.5-3	2.7-3.1	Grey-brown	Black, green-black, brown-black. Transparent to opaque.	Short tablets. Like a tablet of paper.	1 excellent cleavage – splits easily into thin, flexible sheets.	1 flexible cleavage plane (sheet), dark colored; brown streak.
Mica family: **Muscovite** $KAl_3Si_3O_{10}(OH)_2$	2-2.5	2.7-3	White	Colorless, yellow, brown, or red-brown. Transparent to opaque.	Short tablets. Like a tablet of paper.	1 excellent cleavage – splits easily into thin, flexible sheets.	1 flexible cleavage plane (sheet), light colored; white streak.
Chlorite $(Mg,Fe)_{5(}Al,Fe)_2Si_3O_{10}(OH)_8$	2-2.5	2-3	White	Dark or bright green. Opaque.	Short tablets. Like a tablet of paper.	1 excellent cleavage – splits easily into thin sheets.	Green, nonflexible sheets. Very small flakes.
Halite NaCl	2.5	2.1-2.6	White	Colorless, white, yellow, blue, brown, or red. Glassy.	Cubes.	Brittle. 3 excellent cleavage planes at 90° (cubes).	Salty taste. H=2.5. Cubic form and cleavage. Usually clear.
Gypsum $CaSO_4$*2(H_20)	2	2.3	White	Colorless, white, or grey. Translucent to transparent.	Tabular, prisms, blades, or needles.	1 good cleavage plane.	H=2. 1 cleavage plane. Translucent.
Talc $Mg_3Si_4O_{10}(OH)_2$	1	2.7-2.8	White	White, grey, pale green, or brown. Opaque. Greasy or silky luster.	Shapeless masses (if no cleavage visible) or tabular.	1 poor cleavage plane (may not be visible).	Feels greasy or soapy. H=1. Opaque. Not metallic.

Note: Striations and splintery fracture are very similar. They both look like ridges; you can feel the texture of both. Splintery fracture results from breakage (similar to breaking wood and getting splinters); striations usually results from crystal growth. Twinning is more lines, less ridges. It cannot be felt – only seen.

Minerals Prereading Homework

1. Which of these minerals is hardest?
   a. Talc
   b. Calcite
   c. Gypsum
   d. Quartz

2. Which mineral is known for a crystal shape of a dodecahedron?
   a. Quartz
   b. Calcite
   c. Garnet
   d. Plagioclase Feldspar

3. Which of these is NOT a type of luster?
   a. silky
   b. pearly
   c. metallic
   d. soft

4. Which of these minerals is known for a luster that is greasy?
   a. Pyrite
   b. Garnet
   c. Calcite
   d. Talc

5. Which of these minerals does NOT have a high specific gravity?
   a. Pyrite
   b. Magnetite
   c. Graphite
   d. Galena

6. Which of these minerals does NOT have conchoidal fracture?
   a. Plagioclase Feldspar
   b. Quartz
   c. Olivine
   d. Garnet

7. Which of these minerals displays double refraction (splits images when looking through it) AND reacts with acid?
   a. Halite
   b. Gypsum
   c. Talc
   d. Calcite

8. Most minerals come in every color of the rainbow. Which of these minerals does not, and is therefore easily recognizable by its color?
   a. Quartz
   b. Calcite
   c. Plagioclase feldspar
   d. Olivine

9. If mineral A scratches mineral B, mineral A is softer than B. (True / False)
10. Fracture is the tendency of some minerals to break along smooth planar surfaces. (True / False)
11. Most minerals do not display perfect crystal shape. (True / False)
12. Translucent minerals are ones you can see through, like clear glass. (True / False)
13. Streak is the color of a mineral when ground to a powder. (True / False)
14. If a box of quartz weighs 10 kg (precise to ones place), how much does the same volume of corundum weigh?
    (Use specific gravity.) SHOW WORK.
15. If a box of kyanite weighs 10 kg (precise to ones place), how much does the same volume of galena weigh?
    (Use specific gravity.) SHOW WORK
16. Which mineral displays conchoidal fracture, can appear in any color, is hard, glassy, and has a prismatic crystal form?
17. Which mineral displays conchoidal fracture, is usually green, is hard, and appears in aggregates of tiny crystals?
18. Which mineral displays conchoidal fracture, is usually red, is hard, and appears as a 12-sided polygon?
19. Which mineral is usually clear or white, has rhombohedral crystal form, 3 cleavage planes with angles greater and less than 90°, double refraction?

Minerals Lab Exercises

1. For Box A, use the box of materials to determine the hardness of each sample. (Apply hardness tests and give results as limits. Examples: X < 2.5; X > 6.5; 2.5 < X < 3.5. If two or more samples have the same limits, in addition to giving their hardness range as above, ALSO compare them to each other: Examples: A2 < 2.5; A1 < 2.5; A2 < A1.) (*Remember: X > Y means X is greater than Y.*)

	Hardness		Hardness		Hardness
A1		A2		A3	
A4		A5		A6	

2. For Box B, describe the type of cleavage or fracture displayed in each sample. (Be sure to describe what you see, not necessarily what the mineral ID chart suggests!)

	Fracture description (if exists – fracture and cleavage can exist in the same sample)	# of cleavage planes	Angle(s) between cleavage planes (circle)
B1			90º >90º <90º n/a
B2			90º >90º <90º n/a
B3			90º >90º <90º n/a
B4			90º >90º <90º n/a
B5			90º >90º <90º n/a
B6			90º >90º <90º n/a

3. For Box C, describe crystal form **ONLY** of each sample. Use pictures to help. Be specific and detailed. (include number of sides, shape, etc.). (Describe what you see, not what mineral chart suggests!)

	Crystal form description
C1	
C2	
C3	
C4	

4. For Box D, describe the color, luster, & special optical properties of each sample. (Be sure to describe what you see, not necessarily what the mineral ID chart suggests!)

	Luster (and any special opt. props.)	**Color**	**Optical clarity (circle)**
D1			Opaque Translucent Transparent
D2			Opaque Translucent Transparent
D3			Opaque Translucent Transparent
D4			Opaque Translucent Transparent
D5			Opaque Translucent Transparent
D6			Opaque Translucent Transparent

5. For Box E, correctly identify each sample. Describe the diagnostic characteristics of that mineral (include only those that are true for the sample that you are observing, and include enough to distinguish that mineral from any other). **Make your answers unique!**
NOTE: Instead of "very dense or very hard," use the actual hardness and specific gravity numbers.

	Mineral name & formula	**Diagnostic characteristics**
1		
2		
3		
4		
5		
6		
7		
8		
9		

	Mineral name & formula	Diagnostic characteristics
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Observe and describe the diagnostic properties of a provided mineral sample	A | B | C | D | F	
Identify and name rock-forming minerals by hand sample	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Minerals Practice Sheet

Go to the course website flashcards and videos (and come to lab itself) and practice identification of all the different minerals and rocks:
Be sure that for each rock and mineral, you know the environment in which it formed and its distinguishing characteristics.

NOTE: On the exam you will get a list of rock and mineral names, but there is no guarantee that you'll see every rock or mineral OR that you'll see a rock or mineral only once. However, you will NOT see a mixture of rock or mineral types. In other words, all sedimentary rocks will be together – and not mixed with igneous rocks.

For each mineral listed below, give its distinguishing characteristics:

Mineral	**Diagnostic properties**
Pyrite FeS_2	
Magnetite Fe_3O_4	
Hematite Fe_2O_3	
Galena PbS	
Graphite C	
Corundum Al_2O_3	
Garnet $(Ca,Mg,Fe,Mn)_3(Al,Fe,Cr)_2(SiO_4)_3$	
Olivine $(Mg,Fe)_2SiO_4$	
Quartz SiO_2	
Epidote $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$	
Kyanite Al_2SiO_5	
Amphibole family: **Actinolite** $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	
Plagioclase Feldspar family: Anorthite and Labradorite $CaAl_2Si_2O_8$ to Oligoclase and Albite $NaAlSi_3O_8$	

Mineral	Diagnostic properties
Potassium Feldspar family: Orthoclase and Microcline $KAlSi_3O_8$	
Pyroxene family: Augite $Ca(Mg,Fe,Al)(Al,Si)O_6$	
Amphibole family: **Hornblende** $(Ca,Na)_{2-3}(Fe,Mg,Al)_5 Si_6(Si,Al)_2O_{22}(OH)_2$	
Serpentine $Mg_6Si_4O_{10}(OH)_8$	
Fluorite CaF_2	
Calcite $CaCO_3$	
Mica family: **Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	
Mica family: **Muscovite** $KAl_3Si_3O_{10}(OH)_2$	
Chlorite $(Mg,Fe)_5(Al,Fe)_2Si_3O_{10}(OH)_8$	
Halite NaCl	
Gypsum $CaSO_4*2(H_20)$	
Talc $Mg_3Si_4O_{10}(OH)_2$	

MINERAL QUESTIONS

Which minerals are easily distinguished because they can be scratched with a fingernail? (And what are their hardnesses?)	
What minerals are easily distinguished by their distinctive crystal shapes, and what are those shapes?	
What minerals are easily distinguished by their luster? What are their lusters?	
What minerals are easily distinguished by their color? What are their colors?	

What minerals are easily distinguished by their streak? What color are their streaks?	
What minerals are easily distinguished by their density? What are the densities?	
How many times denser are these materials than Quartz (density of 2.7 g/cc)?	
What minerals are easily distinguished by their transparency or translucency?	
What minerals are easily distinguished by their cleavage? What are those cleavages? (# of planes of cleavage and the angle between them)	
What minerals are easily distinguished by their fracture? What are those fracture patterns?	
What mineral can be distinguished by its double refraction (and what does that mean)?	
What mineral can be identified by its reaction with acid?	
If mineral A is scratched BY mineral B, which is harder?	

KEY

For each mineral listed below, give its distinguishing characteristics:

Mineral	**Diagnostic properties**
Pyrite FeS_2	Cubic form, brassy color, and about 2 times denser than the average mineral. Dark grey streak.
Magnetite Fe_3O_4	Attracted to a magnet. About 2 times denser than the average mineral. No cleavage. Dark grey streak.
Hematite Fe_2O_3	Red streak. Metallic + nonmetallic. Earthy red.
Galena PbS	Almost 3 times denser than the average mineral. Silver cubes (form and cleavage). Metallic. Dark grey streak.
Graphite C	Dark grey color and streak. Metallic, greasy luster. Soft enough to scratch with a fingernail.
Corundum Al_2O_3	H=9. (Harder than anything but diamond.) Barrel-shaped, flat-end hexagons.
Garnet $(Ca,Mg,Fe,Mn)_3(Al,Fe,Cr)_2(SiO_4)_3$	Dodecahedron form, red (sometimes), glassy, conchoidal fracture, harder than glass.
Olivine $(Mg,Fe)_2SiO_4$	Green, conchoidal fracture, glassy, harder than glass.. Usually granular. Not a hexagonal crystal.
Quartz SiO_2	Glassy, conchoidal fracture, harder than glass.. Hexagonal prism with pointed end.
Epidote $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$	Harder than glass. Green. Striated crystal faces. Massive. NOT needles.
Kyanite Al_2SiO_5	Blue, flexible blades.
Amphibole family: **Actinolite** $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	Green, thin needles.
Plagioclase Feldspar family: Anorthite and Labradorite $CaAl_2Si_2O_8$ to Oligoclase and Albite $NaAlSi_3O_8$	Twinning. 2 cleavages at 90°. Softer than glass – harder than a nail. Often displays blue iridescence.
Potassium Feldspar family: Orthoclase and Microcline $KAlSi_3O_8$	Subparallel exsolution lamellae. 2 cleavages at 90°. Pink or white color. Softer than glass – harder than a nail. No twinning.
Pyroxene family: Augite $Ca(Mg,Fe,Al)(Al,Si)O_6$	Softer than glass, about as hard as a knife. Mostly black (or dark green). 2 cleavages at 90°. (Looks like Hornblende, but without the splintery fracture.)
Amphibole family: **Hornblende** $(Ca,Na)_{2\text{-}3}(Fe,Mg,Al)_5$ $Si_6(Si,Al)_2O_{22}(OH)_2$	Softer than glass, about as hard as a knife. Mostly black. 2 cleavages at 60° & 120°. Splintery fracture. Long prisms.
Serpentine $Mg_6Si_4O_{10}(OH)_8$	Mottled green color. Smooth, curved surfaces. No cleavage. Can't be scratched with a fingernail. Can be scratched with a nail or knife. Waxy luster.
Fluorite CaF_2	Cubic or octahedral form. 4 directions of cleavage. Triangular faces. Rainbow luster in places.
Calcite $CaCO_3$	Bubbles in HCL. Double refraction (2 images visible through clear sample). Rhombs, 3 cleavage planes (not 90°), H=3.
Mica family: **Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	1 flexible cleavage plane (sheet), dark colored; brown streak.
Mica family: **Muscovite** $KAl_3Si_3O_{10}(OH)_2$	1 flexible cleavage plane (sheet), light colored; white streak.
Chlorite $(Mg,Fe)_5(Al,Fe)_2Si_3O_{10}(OH)_8$	Green, nonflexible sheets. Very small flakes.
Halite NaCl	Salty taste. Can't be scratched with a fingernail. Can be scratched with brass, a nail, or a knife . Cubic form and cleavage.

Mineral	Diagnostic properties
Gypsum $CaSO_4*2(H_20)$	Can be scratched with a fingernail. 1 cleavage plane. Translucent.
Talc $Mg_3Si_4O_{10}(OH)_2$	Feels greasy or soapy. Can be scratched with a fingernail. Opaque. Not metallic.

MINERAL QUESTIONS

Which minerals are easily distinguished because they can be scratched with a fingernail? (And what are their hardnesses?)	Talc (1); Gypsum (2), Graphite (1)
What minerals are easily distinguished by their distinctive crystal shapes, and what are those shapes?	• Hexagonal prism ending in a point -- Quartz • 12-SIDED – Garnet • CUBIC – Halite, Galena, sometimes Fluorite • Calcite – Rhombohedron BLADES: Kyanite OCTAHEDRON (eight-sided polygon) Fluorite TABULAR (like a tablet of stone or paper): Talc, MICAS: Biotite or Muscovite, often Gypsum NEEDLES: Actinolite
What minerals are easily distinguished by their luster? What are their lusters?	METALLIC: Galena, Pyrite, Graphite, Hematite, Magnetite GLASSY (or vitreous): Quartz, Calcite, Garnet, Olivine GREASY: Graphite PEARLY: MICA: Muscovite or Biotite GREASY to PEARLY: Talc SILKY and SATINY: Gypsum SILKY, WAXY, and GREASY: Serpentine METALLIC and NONMETALLIC (depending on surface you're observing) Hematite
What minerals are easily distinguished by their color? What are their colors?	**green**: Olivine **red:** Garnet (usually red, but can also be brown or green) Hematite (earthy red and metallic grey, but always has a red streak) **pink**: Potassium (K) Feldspar (can also be white) **blue**: Kyanite **gold:** Pyrite
What minerals are easily distinguished by their streak? What color are their streaks?	• Pyrite, Magnetite, Graphite, Galena – Dark Grey Streak • Hematite – Red Streak, Biotite – Brown streak
What minerals are easily distinguished by their density? What are the densities?	7.6 g/cc – Galena 5.2 g/cc – Magnetite 5 g/cc – Pyrite
How many times denser are these materials than Quartz (density of 2.7 g/cc)?	• Galena – 2.8 times denser than quartz • Magnetite and Pyrite – 1.9 times denser than quartz
What minerals are easily distinguished by their transparency or translucency?	Gypsum, Calcite, Quartz, Garnet, Halite, Fluorite, Olivine, thin flakes of micas
What minerals are easily distinguished by their cleavage? What are those cleavages? (# of planes of cleavage and the angle between them)	One direction of cleavage, perfect (sheets) Muscovite or Biotite or Chlorite Two directions of cleavage at 90 degrees: Feldspar, Pyroxene Three directions of cleavage, not at 90 degrees: Calcite Three directions of cleavage at 90 degrees (cubes): Halite, Galena 4 directions of cleavage, not at 90 degrees: Fluorite
What minerals are easily distinguished by their fracture? What are those fracture patterns?	Olivine, garnet, and quartz are well known for their conchoidal fracture. Hornblende is known for its splintery fracture:
What mineral can be distinguished by its double refraction (and what does that mean)?	Calcite – placed atop text, you can see two images.
What mineral can be identified by its reaction with acid?	Calcite
If mineral A is scratched BY mineral B, which is harder?	Mineral B

Igneous Rocks

Magma is molten rock below the surface. **Lava** is molten rock that is now exposed at the surface. **Igneous rocks** are rocks that form from the solidification of magmas. (All igneous rocks were once molten.)

Generating magmas

Most magmas form at great depth when mantle rock partially melts. Mantle rock is ultramafic in composition and solid under its usual pressure and temperature conditions. Its minerals are stable in solid form (like food in an icebox). To melt mantle rock, there must be a change in the normal conditions. If temperature increases for example, some of the minerals in the mantle rock will start to melt (not all, just some – think of increasing the temperature in your freezer – not everything starts to melt at once). If pressure decreases or water is added (or both), the melting point of a mineral actually decreases and it will start to melt. As small amounts of melt migrate and accumulate, they form a magma.

Imagine taking a jar and filling it with marshmallows, water, and syrup. Now freeze it. The composition of the jar is the combined composition of all three ingredients. But if you increase the temperature of the jar slightly, so that some components are still frozen and others not, (say the water melts only), then you get a melt forming that has a different overall composition from the jar's materials. The original composition was marshmallows, water, and syrup. The melt that forms from a slight increase in temperature is pure water. The residual material left behind is marshmallows and syrup (no water).

The same thing happens in the mantle. When ultramafic mantle rock begins to melt, only minerals with the lowest melting temperatures go into the magma phase. Others remain behind. We call this **partial melting**. We can study the composition of mantle rocks and tell if they've produced melts before. (If our jar contains only marshmallows and syrup, then we know it partially melted and lost its water.)

To melt mantle rock, there must be a drop in pressure (which is what happens under oceanic ridges where seafloor spreading occurs), a rise in temperature (which is what happens when plumes migrate from the deep in the Earth, through the mantle and the crust), or an influx of water (which happens where subduction zones reinject water-rich oceanic crust back into the mantle).

Partially melted mantle tends to produce mafic compositions. Fully melted mantle produces ultramafic magmas. After these magmas are produced at depth, they rise because of buoyancy.

Changing magma composition

As magmas rise, they mix with other magmas (**magma mixing**) or melt rocks that they are moving through (**assimilation**), both of which processes will change magma composition. In addition, as magmas rise to the surface, they gradually cool down. When magmas cool, crystals start to form. Bowen's Reaction Series is a graphic representation of the order in which minerals crystallize during the cooling of a typical ultramafic magma (see image ahead). If after a mineral forms it is removed from the magma through gravitational settling or floating or other processes, the magma composition will change. We call this process **crystal fractionation**. Back to our frozen jar example from earlier, imagine that we have a molten goop of chocolate, marshmallows, and water. If the marshmallows are the first to cool and solidify from the goop, and after they solidify, they float to the top, removing themselves from the goop, the goop's composition is now different. It began with 1/3 marshmallow. Now it has none! Magma composition changes when particular elements are removed to form early minerals. Most early minerals like olivine, plagioclase and pyroxene contain high amounts of (iron) Fe, (magnesium) Mg, and (calcium) Ca, and low amounts of silicon. Thus, early crystal fractionation removes iron, magnesium, and calcium from the magma, leaving the magma preferentially enriched in silicon and sodium.

If a high-temperature mineral crystallizes and remains in the melt (as opposed to settling out of the magma due to gravity), it will react with the remaining magma to become a different mineral. There are two types of reaction series for minerals: the Fe-Mg silicates are the discontinuous branch, while the plagioclase feldspars form the continuous branch. In the discontinuous reaction series, as the magma cools each mineral reacts with the remaining more evolved magma to form a different mineral. For example, olivine reacts with an evolving magma to form pyroxene. The continuous branch involves the continuous reaction of plagioclase feldspar with the melt to change its composition only, not its crystal structure. Plagioclase gets more sodium-rich during magma evolution. Bowen's Reaction Series provides a useful way to describe which minerals, because of similar temperatures of crystallization, are found together in a given igneous rock. Draw a horizontal line through the Bowens Reaction Series at any point and you will find the minerals that can coexist in an igneous rock of that specific composition.

Occasionally magmas carry pieces of foreign rocks that are caught up in the magma when it moves through and breaks surrounding rock. Such foreign rocks are called **xenoliths**.

Magma chambers are areas in the crust where magmas accumulate and reside for long periods of time. Magmas in these chambers can erupt at any time – usually when new magmas rise under them and push them out. Since magma compositions can change so easily over time, the composition of erupted lavas or plutons from a single volcano can also vary.

Primitive magmas (ones that haven't experienced much evolution through crystal fractionation) are dominant in seafloor spreading centers (where oceanic crust is thin and so primitive magmas can reach the surface quickly). ***Evolved*** magmas dominate in continental volcanism (where continental crust is thick, and magmas take a long time to reach the surface on their journey from the mantle and can undergo changes).

The word *mafic* comes from the abundance of *magnesium* and iron (*Fe*). The world *felsic* comes from the large percentage of *feldspars* and *silicon* in their mineral composition. Bowen's reaction series shows how primitive, **ultramafic** magmas change into evolved, **felsic** magmas, as the Mg- and Fe-rich minerals crystallize first and are removed from the magma. (Along the way, they evolve into first **mafic**, then **intermediate** compositions.) Ultramafic magmas and their solidified rock forms are extremely rare, because their magmas must have undergone no changes on their way to the surface.

You can use Bowen's Reaction Series to see what minerals crystallize in each composition magma. Primitive magmas produce olivine and pyroxene. Evolved magmas produce mostly potassium feldspar and quartz.

Volcanic (or extrusive) igneous rocks

Magmas that reach the surface and erupt as lavas ultimately form **extrusive** rocks. We classify extrusive rocks by the eruption style and the composition of the magmas. **Basalts** are the products of mafic lavas. **Rhyolites** are the products of felsic lavas. **Andesites** are intermediate. (Note: Ultramafic lavas don't exist on Earth anymore, as our crust it too thick, even in the oceans, to allow no evolution to occur during magma transit). When lavas erupt at the surface, they cool too quickly for visible crystals to form (though there are crystals in the rocks, just too small to see). We call the texture of these rocks **aphanitic** (most crystals are too small to see). Note:

Any large crystals found in volcanic rocks were produced at depth in the magma chamber (imagine a few minerals just beginning to slowly form throughout the magma – they'd be scattered, like poppy seeds in a muffin). These crystals are carried to the surface during the eruption. Volcanic rocks that consist of an aphanitic (or small-crystal size) matrix or **groundmass** with larger crystals disseminated throughout that groundmass, like chocolate chips in a cookie are called **porphyritic**. Sticking with the chocolate chip cookie analogy, the chips are called **phenocrysts**; they formed when the magma was still underground (prior to eruption); the rest of the cookie is the groundmass; it formed after eruption. Most volcanic rocks display a porphyritic texture in some form. We name such rocks by preceding the name with the major phenocryst and ending the name with the word, porphyry. Example: olivine basalt porphyry.

The more evolved the magma (felsic), the more silica, and hence the more viscous the fluid. (Viscosity is a measurement of a fluid's resistance to flow: syrup is more viscous than water.) As viscosity increases, it becomes harder to produce crystals (ions have a hard time moving through the melt to find each other). Occasionally, extremely evolved magmas produce lavas that are so viscous that they cool before they can produce any crystals. When no crystals form, we call the substance **glass**. Felsic lavas that cool as glass are called **obsidian**. Glass usually forms when lavas either cool too quickly to form crystals, or when the lava is so viscous that ions can't move to form crystals.

Magmas also can contain a lot of gas (water, sulfur dioxide, carbon dioxide, etc.). When such lavas erupt, a process occurs that is similar to opening the top on a can of shaken soda. The gas immediately wants to get out of the lava. As lavas flow across the surface, these gases rise through the lava. When the lava cools and solidifies around gases, the final rock contains **vesicles**, small round pockets in the rock, where gas was trapped while moving.

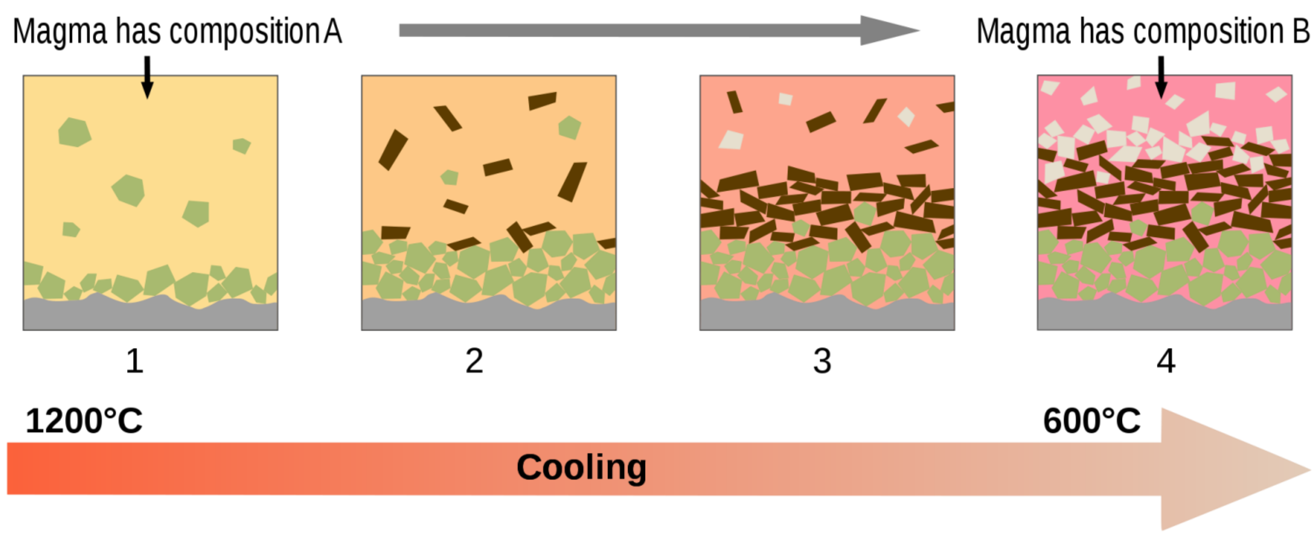
When erupted lavas contain more vesicles than rock, they have a **frothy** texture (lightweight – mostly holes – with the actual rock made of glass – no minerals – quickly cooled). Frothy rocks are called **pumice** if they're light colored (and therefore felsic or intermediate in composition) or **scoria** if they're dark colored (and therefore mafic in composition). Because mafic compositions have iron in them, scoria is not light enough to float in water. Pumice, however, does!

Lavas that contain more gas than liquid will erupt violently as **ash**. Ash is just a tiny drop of liquid that adheres to the exsolving gas bubbles and solidifies into glass (no crystals) as soon as it hits the air. Ash (as well as particles pumice, crystals, and other volcanically ejected material – collectively called **pyroclastic** debris) can accumulate on the surface of volcanoes. When this material is compressed or welded together, it forms a rock called **Tuff**. Pyroclastic rocks are made of pieces (*clasts*) of material that came from a volcano or fire (*pyro*).

Plutonic (or intrusive) igneous rocks

Magmas that never reach the surface will cool at depth in a magma chamber or vein or dike. As long as they are deep, they cool slowly and form large crystals (crystal size increases with slower cooling). Slowly cooling mafic magmas produce **gabbro** (the plutonic equivalent of a basalt). Slowly cooling felsic magmas produce **granite** (the plutonic equivalent of rhyolite). Intermediate magmas produce **diorite** (the plutonic equivalent of andesite) . We call the texture of these larger-crystalline rocks **phaneritic** (100% crystals visible to the eye).

We attach the term **pegmatite** to any plutonic rocks with *unusually* large crystals. Pegmatites form because cooling was slow and water content was extremely high, thereby decreasing magma viscosity and allowing ions to migrate quickly. To name such rocks, we append the word, pegmatite, to the end of the rock name. Example: granite pegmatite.



Schematic diagrams showing the principles behind fractional crystallization in a magma. While cooling, the magma evolves in composition because different minerals crystallize from the melt. 1: olivine crystallizes; 2: olivine and pyroxene crystallize; 3: pyroxene and plagioclase crystallize; 4: plagioclase crystallizes. At the bottom of the magma reservoir, a cumulate rock forms. Image: Woudloper – Creative Commons – CC BY-SA 3.0

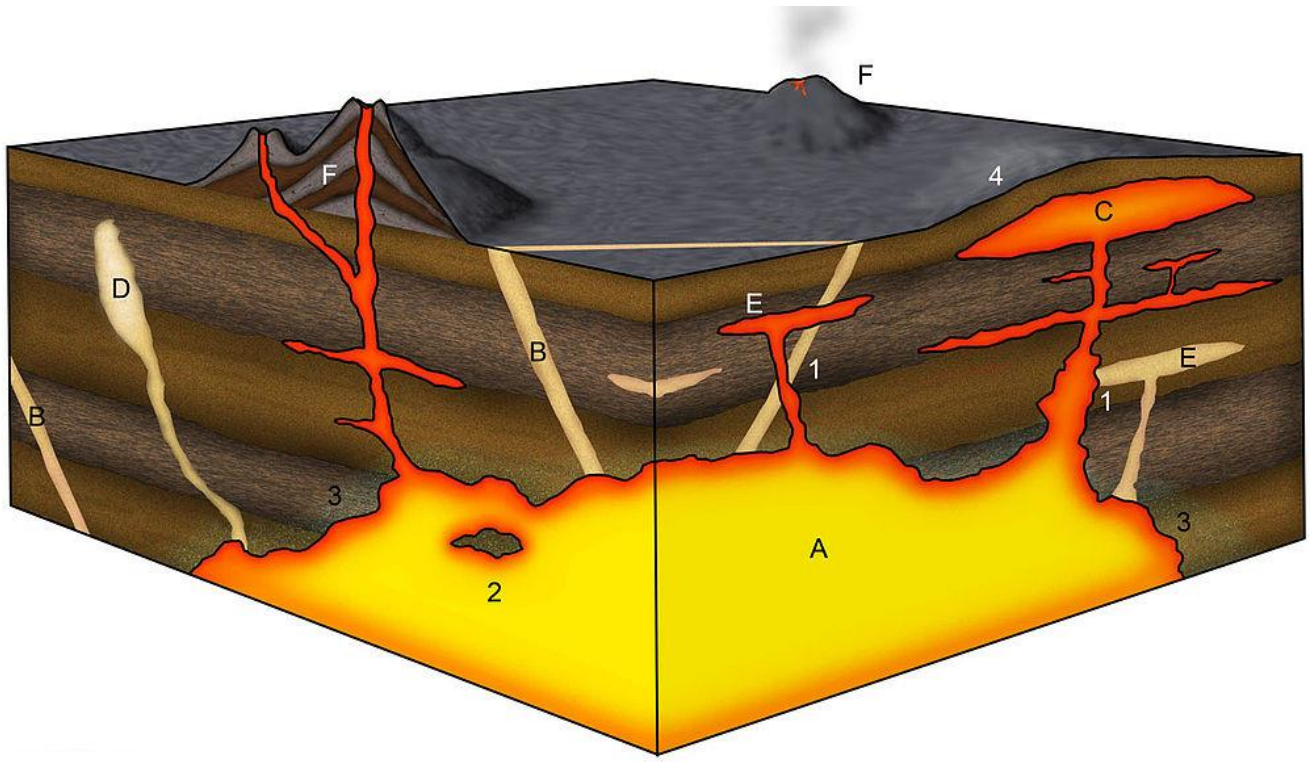


Diagram showing volcanic and intrusive structures. Schematic overview of igneous and volcanic structures/bodies. A = magma chamber (batholith); B = dyke/dike; C = laccolith; D = pegmatite; E = sill; F = stratovolcano; processes: 1 = newer intrusion cutting through older one; 2 = xenolith or roof pendant; 3 = contact metamorphism; 4 = uplift due to laccolith emplacement. Image: Woudloper – Public Domain

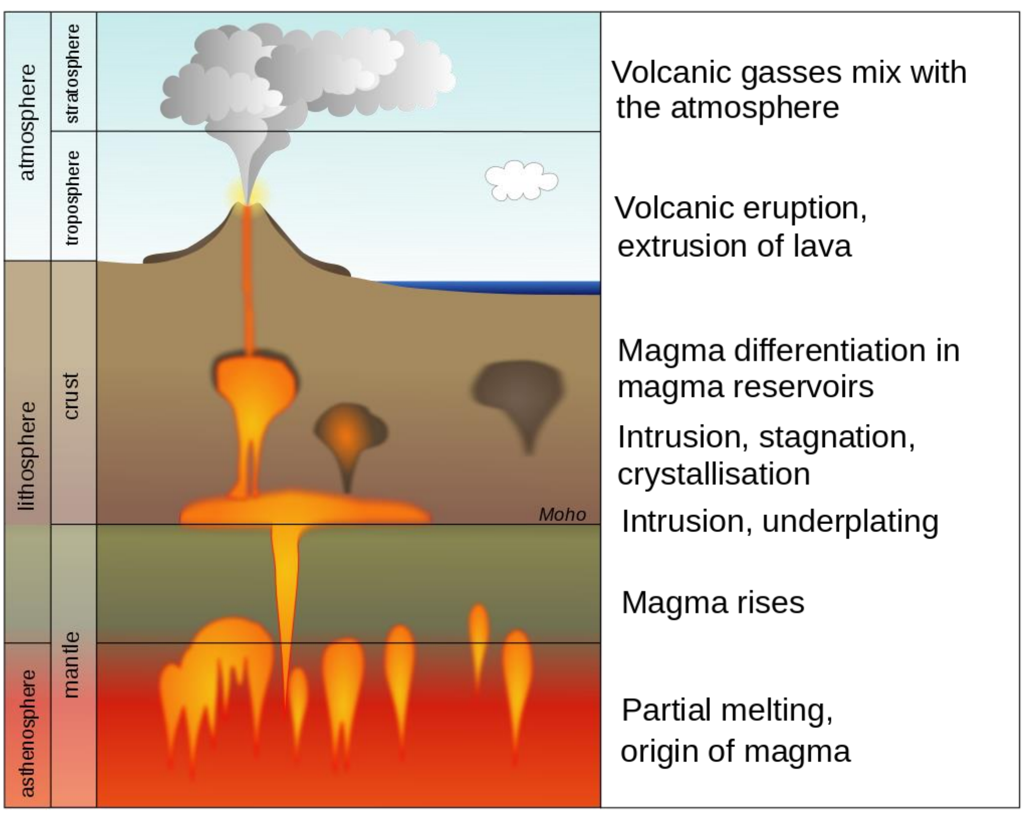


Image: Woudloper –Creative Commons – CC BY-SA 3.0

Igneous Rock Characterization and Identification

To identify (name) igneous rocks, you determine two things about the rock: composition and texture. First determine composition, which is based on mineral content or color, if you can't see minerals. Then determine the texture of the rock and based on the two, identify the rock name.

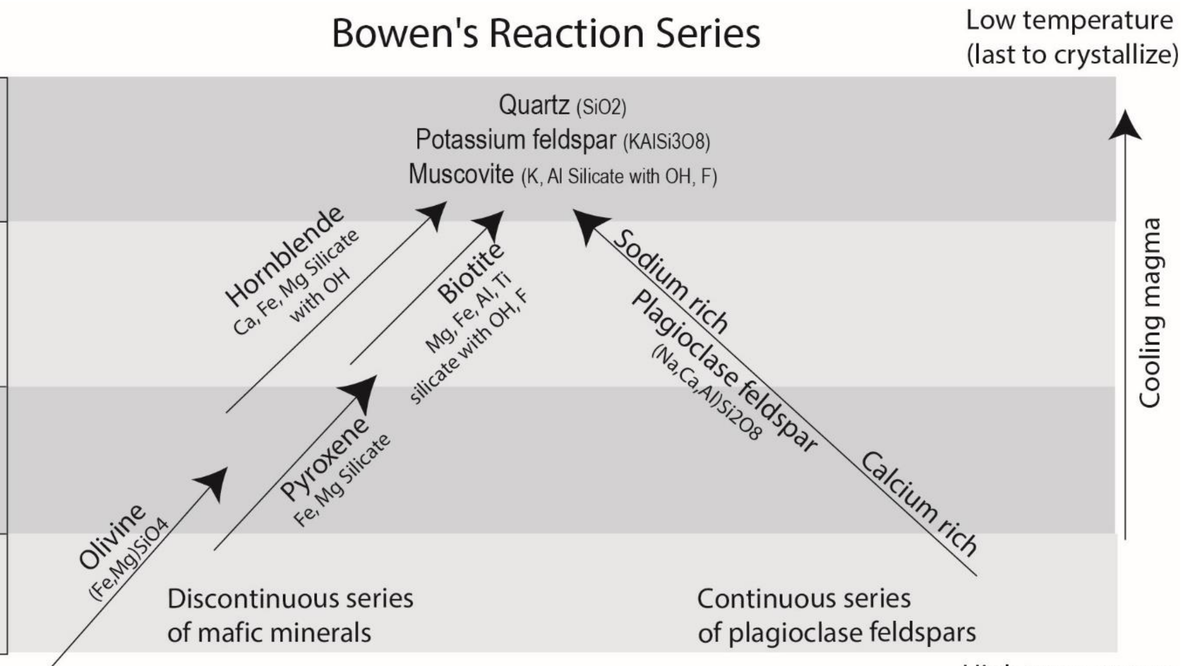
Composition									
Quartz	Potassium Feldspar	Muscovite	Biotite	Hornblende	Plagioclase	Pyroxene	Olivine	Color index (if can't see minerals)	Compositional name
0	0	0	0	0	0-20%	0-20%	50-100%	Very dark	Ultramafic
0	0	0	0	0-10%	20-60%	25-30%	0-50%	Dark	Mafic
0	0	0	0-5%	10-20%	10-60%	0-10%	0	Grey (medium dark)	Intermediate
10-30%	0-50%	0-5%	0-5%	0-10%	10%	0	0	Very light to salt and pepper colored (can contain a lot of pink)	Felsic

	Texture				
	Phaneritic 100% visible crystals	Aphanitic Most crystals too small to see	Glassy 100% glass	Frothy Greater than 50% vesicles (rest is usually glass)	Pyroclastic Fragments of ash, crystals, pumice, rocks
Ultramafic	Peridotite				
Mafic	Gabbro	Basalt		Scoria	Volcanic Tuff
Intermediate	Diorite	Andesite		Pumice	Volcanic Tuff
Felsic	Granite	Rhyolite	Obsidian	Pumice	Volcanic Tuff
	Pegmatitic texture is a subcategory of Phaneritic (see below for naming information)	*Porphyritic texture is a subcategory of Aphanitic (see below for naming information)*			

Add PEGMATITE to the name IF the rock displays pegmatitic texture: If an intrusive igneous rock has extremely large minerals (> 2 inches long), the rock is called a **pegmatite**. (Naming examples: granite pegmatite) **NOTE**: All pegmatites are phaneritic rocks.

Add PORPHYRY to the name IF the rock displays porphyritic texture. If an aphanitic igneous rock has *phenocrysts* in it (large minerals surrounded by an aphanitic matrix), it is called **porphyritic**. Add the name of the prominent phenocryst mineral to the front of the rock name. (Naming example: olivine basalt porphyry) **NOTE**: All porphyries are aphanitic rocks, because the majority of the rock (the groundmass, or matrix) is aphanitic.

COMPOSITION NAME	APHANITIC ROCK NAME	PHANERITIC ROCK NAME
Felsic	Rhyolite	Granite
Intermediate	Andesite	Diorite
Mafic	Basalt	Gabbro
Ultramafic		Peridotite



Example: A mafic rock contains pyroxene and plagioclase and possibly small amounts of olivine. If a mafic rock is volcanic, we call it basalt. If it is plutonic, we call it gabbro.

Igneous Rocks Prereading Homework

1. Which types of magmas are most common in seafloor spreading centers?
   a) Primitive
   b) Evolved
   c) Neither

2. Why?
   a) Crust is thick
   b) Crust is thin
   c) Lots of water
   d) Low pressure

3. Primitive magmas produce which one of these minerals?
   a) Olivine
   b) Quartz
   c) Potassium Feldspar
   d) Muscovite

4. Evolved magmas produce which one of these minerals?
   a) Quartz
   b) Pyroxene
   c) Plagioclase Feldspar
   d) Olivine

5. Which of these is NOT a method for melting mantle rock?
   a) Increase temperature
   b) Decrease pressure
   c) Add water
   d) None – all are valid methods

6. What's the composition of obsidian?
   a) Felsic (rhyolite)
   b) Intermediate (andesite)
   c) Mafic (basalt)
   d) None of the above

7. What do we call the texture of a volcanic rock when there are more holes in the rock than rock itself?

8. What do we call the texture of an igneous rock composed of fragments of erupted materials?

9. What do we call the texture of an igneous rock when there are unusually large crystals?

10. What do we call the texture of an igneous rock when there are two separate sizes of minerals: a background groundmass with small crystals, usually too small to see, and a few scattered larger crystals, like a chocolate chip cookie?

11. Which igneous rock forms from the eruption of magmas in seafloor spreading centers?

12. Which igneous rock forms from the slow cooling of the most evolved magmas at depth under volcanoes?

13. Which igneous rock is 100% glass, with little or no vesicles (felsic composition)?

14. Which igneous rock is made of pyroclastic material of any composition?

15. What's wrong with this rock name: Potassium-feldspar Andesite Porphyry.

Igneous Rocks Lab Exercises

1. For Box A, name any minerals that you can identify. Estimate the percentage of that mineral in the sample. (Use Bowen's Reaction Series to review what minerals can be found together.) Note: if visible minerals are only phenocrysts, be sure to indicate such, and give percentages for just the phenocrysts (so they add to 100%). Do not estimate the percentage of minerals in the groundmass if aphanitic.

Sample #	**Mineral names and percentages**	**Composition (circle)**
4004		Ultramafic/Mafic/Intermediate/Felsic
4035		Ultramafic/Mafic/Intermediate/Felsic
4071		Ultramafic/Mafic/Intermediate/Felsic
4128		Ultramafic/Mafic/Intermediate/Felsic
6		Ultramafic/Mafic/Intermediate/Felsic
Ice 9		Ultramafic/Mafic/Intermediate/Felsic

2. For Box B, describe the textures of the various rocks. Use proper terms: glassy, frothy, vesicular, phaneritic, aphanitic, or pyroclastic. Also indicate if porphyritic or pegmatitic and if so, use a ruler to estimate the size of the largest crystals.

Sample #	**Textural description**	**Type (circle)**
1		Intrusive/Extrusive
3		Intrusive/Extrusive
4100		Intrusive/Extrusive
14		Intrusive/Extrusive
4072		Intrusive/Extrusive

3. FINAL ID BOX: Correctly identify each sample. Describe diagnostic characteristics of that particular sample. Make them unique! If any description can apply to more than one rock, you haven't found the right description!

<u>Use this checklist to help and record diagnostic properties.</u>

□ Pyroclastic Texture; □ Frothy Texture, Dark Colored; □ Frothy Texture, Light Colored □ Glassy Texture
□ Phaneritic Texture or □ Aphanitic Texture AND presence of mostly these minerals:
□ Quartz, Potassium Feldspar, Muscovite (Felsic -- light) □ Biotite, Hornblende, Plagioclase (Intermediate) □ Pyroxene, Plagioclase (mafic – dark); □ Olivine (ultramafic) (Use color ONLY if no minerals present!)

Sample	Rock name	Diagnostic characteristics (specific texture and minerals – or color IF no minerals present)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Observe and describe textures and composition of a provided igneous rock sample	A | B | C | D | F	
Identify and name igneous rocks by hand sample	A | B | C | D | F	
Compare and contrast textures and compositions of igneous rocks and what they indicate about the formation of a rock	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Igneous Rocks Practice Sheet

Go to the course website flashcards and videos (and come to lab itself) and practice identification of all the different minerals and rocks.
Be sure that for each rock and mineral, you know the environment in which it formed and its distinguishing characteristics.

NOTE: On the exam you will get a list of rock and mineral names, but there is no guarantee that you'll see every rock or mineral OR that you'll see a rock or mineral only once. However, you will NOT see a mixture of rock or mineral types. In other words, all sedimentary rocks will be together – and not mixed with igneous rocks.

Igneous rock name	**Texture**	**Composition (if it's a phaneritic rock, be sure to include here the actual minerals present)**	**INTRUSIVE OR EXTRUSIVE**
Peridotite			
Gabbro			
Diorite			
Granite			
Basalt			
Andesite			
Rhyolite			
Volcanic Tuff			
Scoria			
Pumice			
Obsidian			

IGNEOUS ROCKS QUESTIONS

Primitive magmas are associated with what kind of geologic setting and crust?	
Primitive magmas are associated with what minerals?	
Evolved magmas are associated with what kind of geologic setting and crust?	
Evolved magmas are associated with what minerals?	
What minerals are found together in intermediate composition rocks?	
So… list 2-mineral pairs that would never be found together in igneous rocks (but ARE igneous minerals).	
What igneous texture contains only felsic rocks? What is the name of the rock?	
What are the three ways for melting mantle rock?	
What's the difference between a frothy igneous rock and a vesicular one?	
What's the complete name of a granite that contains unusually large crystals?	
What's the complete name of an andesite with hornblende phenocrysts?	

KEY

Igneous rock name	Texture	Composition (if it's a phaneritic rock, be sure to include here the actual minerals present)	INTRUSIVE OR EXTRUSIVE
Peridotite	Phaneritic	Olivine mostly – some pyroxene and plagioclase OK	Intrusive
Gabbro	Phaneritic	Mostly pyroxene and plagioclase – some olivine	Intrusive
Diorite	Phaneritic	Mostly hornblende and biotite and plagioclase	Intrusive
Granite	Phaneritic	Mostly quartz, muscovite, K-feldspar (some hornblende, biotite, and plagioclase)	Intrusive
Basalt	Aphanitic	Dark and dense (might contain phenocrysts of olivine or plagioclase)	Extrusive
Andesite	Aphanitic	Medium-colored and density (might contain phenocrysts of hornblende)	Extrusive
Rhyolite	Aphanitic	Light-colored and lower density (might contain phenocrysts of quartz or potassium feldspar)	Extrusive
Volcanic Tuff	Pyroclastic	Pumice, ash, crystals, rocks (clastic)	Extrusive
Scoria	Frothy	Dark and dense	Extrusive
Pumice	Frothy	Light color and low density (floats on water)	Extrusive
Obsidian	Glassy	No crystals	Extrusive

IGNEOUS ROCKS QUESTIONS

Primitive magmas are associated with what kind of geologic setting and crust?	Oceanic volcanism – hotspots, spreading center – thin crust
Primitive magmas are associated with what minerals?	Olivine, plagioclase, maybe pyroxene
Evolved magmas are associated with what kind of geologic setting and crust?	Continental volcanism – subduction zones – thicker crust
Evolved magmas are associated with what minerals?	Quartz, potassium feldspar, Muscovite
What minerals are found together in intermediate composition rocks?	Biotite, Hornblende, Plagioclase
So… list 2-mineral pairs that would never be found together in igneous rocks (but ARE igneous minerals).	Olivine and quartz, potassium feldspar, muscovite, biotite, hornblende, pyroxene and quartz, potassium feldspar, muscovite, biotite
What igneous texture contains only felsic rocks? What is the name of the rock?	Glassy, Obsidian
What are the three ways for melting mantle rock?	Raise temperature; Add water; Drop pressure
What's the difference between a frothy igneous rock and a vesicular one?	>50% vesicles (FROTHY) <50% (VESICULAR)
What's the complete name of a granite that contains unusually large crystals?	Granite pegmatite
What's the complete name of an andesite with hornblende phenocrysts?	Hornblende andesite porphyry

Sedimentary Rocks

Sedimentary rocks form from:

- **Precipitation** of minerals directly from a fluid (example: salt that forms when seawater evaporates).
- **Lithification of sediment** – small particles of rocks, minerals, and organic material, broken up, transported, and deposited in piles, then hardened and turned into rocks through:
  - **Cementation** of sediments usually by aqueous solutions that percolate through sediments and deposit calcite, quartz, or iron oxide glues that then cement the sediments together. Example: sand dunes buried and cemented by percolating waters depositing quartz or calcite between grains to create *sandstone*.
  - **Compaction** of sediments by being buried under layers of other rocks and sediments. Example: old layers of seafloor mud buried under new layers, thereby becoming mudstone and shale.

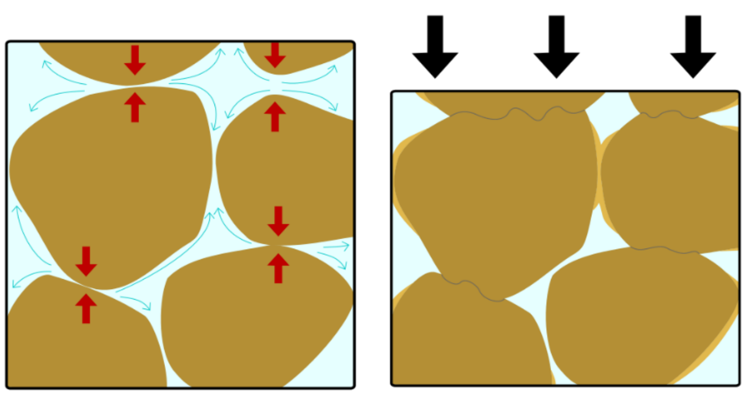
Classifying sedimentary rocks

Composition and grain size are the primary means for classifying sedimentary rocks. All sedimentary rocks are separated into these main categories:

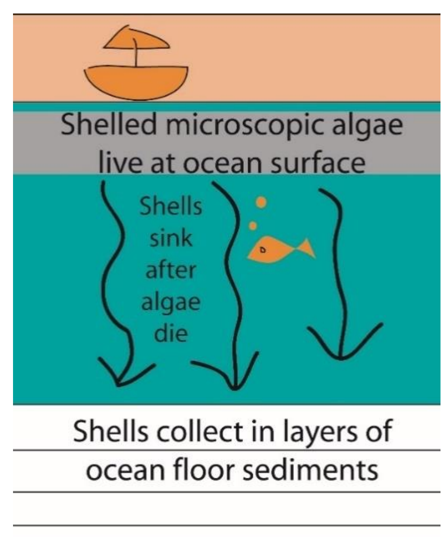
- **Chemical** – Intergrown crystals precipitated from *aqueous solutions* (water and dissolved ions): gypsum, halite, limonite, hematite, dolomite, some varieties of quartz, calcite.
- **Clastic** – Composed of individual fragments (clasts), usually of varying types of material.
  - **Organic** – Fragments that are mostly the remains of organisms: shells, plant fragments, carbon.
  - **Detrital** – Fragments that are mostly rock fragments and mineral grains that were weathered and transported from their source – broken pieces, of quartz, feldspars, micas, clays, and rocks.

Chemical sedimentary rocks can have a **crystalline** texture (visible crystals) or **microcrystalline** texture (crystals too small to see). We further classify chemical sedimentary rocks by their primary mineral composition. For example, chemical sedimentary rocks of $CaCO_3$ composition (like the mineral Calcite) are called **limestones**. If the composition is mostly SiO_2 (glass), they are called **chert**.

Clastic sedimentary rocks are classified by both their composition and their grain size. For example, rocks with mud-sized fragments of calcareous ($CaCO_3$) shells are called **chalk**. Rocks with mud-sized fragments of siliceous (SiO_2) shells are called **diatomite**. Rocks with mud-sized fragments of detritus (rocks, minerals, etc.) are called **mudstones**.



Schematic diagram of pressure solution accommodating compression/compaction in a clastic rock. Left box shows the situation before compaction. Blue arrows indicate the flow of particles in solution. Red arrows indicate areas of maximum stress (= grain contacts). Right box shows the situation after compaction. In light colored areas new mineral growth has reduced pore space. Image: Woudloper – Public Domain.



Chalk or diatomite formation

Grain shape	Grain size
Angular (edges are mostly angular) Subangular (edges are both rounded and angular, but more of the latter) Subrounded (edges are both rounded and angular, but more of the former) Rounded (edges are mostly rounded, but shapes are not necessarily spherical) Well rounded (like perfect spheres)	Gravel (>2 mm) Coarse sand Medium sand Fine sand Mud (<1/16 mm)
Sorting	
Very poorly sorted (very wide range of sizes – like gravels of all sizes, mixed with sand and mud) Poorly sorted (wide range of sizes – like small gravels mixed with sand and possibly mud) Moderately sorted (moderate range of sizes -- like coarse-to-fine sands, and some mud-sized grains) Well sorted (narrow range of grain sizes, like all mud-sized, or medium to coarse-grained sands) Very well sorted (narrowest range of grain sizes, like all the finest size of mud, or all fine-grained sands)	

Grain size – Grains are largest near their **source** (exposed bedrock region, where first weathered off parent rock). As grains are moved away from their source by water or gravity, they continue to break down, becoming smaller. While small grains are easily transported, only high-energy water can transport large grains.

- **Gravel** – Probably close to source. Moved and deposited only by high-energy waters, like floods; typically found near exposed bedrock in mountainous areas or at the base of eroding cliffs and headlands.
- **Sand** – Probably far from source. Deposited by moderate-energy waters, like rivers or surf; typically found on beaches or river bars. Further divided into coarse, medium, and fine grained.
- **Mud** – Probably very far from source. Deposited by low-energy waters, like lakes, lagoons, and the bottom of the seafloor.

Grain sorting (degree of similarity of grain sizes) **–** As grains are transported by water and deposited wherever the water slows, they sort themselves by size and weight. The longer they've been carried, the better the sorting. {Wind deposits are very well sorted, but only because wind can transport only a very narrow range of fine sands. Glaciers carry all grain sizes far from their source without significantly reducing size. They deposit their load by simply dropping it as the ice melts. Therefore, glacial deposits are very poorly sorted. Landslide deposits are also poorly sorted.}

- **Very poorly sorted** – Probably very close to source, with no transit by water.
- **Poorly sorted** – Probably close to source, with little if any transit by water.
- **Moderately sorted** – Probably far from source, with some transit by water.
- **Well sorted** – Probably far from source, with extensive transit by water.
- **Very well sorted** – Probably very far from source, with extensive transit by wind or water.

Grain shape – As grains are transported by wind or water or if they have water continually running across them (like waves moving across sand and pebbles at the beach), they knock against each other and round. When grains are first weathered from their parent rock, they are jagged. The degree of rounding is a good indicator of how much wind transport or water transport or wave motion has occurred or after initial grain formation. {Wind rounds and frosts only sand-sized grains. Glaciers trap sediment in ice, preventing rounding.}

- **Angular** – Probably very close to source. Little if any transit by water.
- **Subangular** – Probably close to source. Some transit by water.
- **Subrounded** – Moderate distance from source. Moderate transit by water.
- **Rounded** – Probably far from source. Significant transit by water.
- **Well rounded** – Probably very far from source. Major transit by water.

Grain composition – As grains break off their parent rock, they are also undergoing chemical weathering. The longer a grain has been separated from its source, the more exposure it has had to the elements, and the more weathered it will be. We call the young grains immature, and the older ones mature. The range of grain composition found in sediment is a good indicator of maturity *(or the length of time a sediment grain has been around).*

- **Quartz** – Mature; withstands chemical weathering. Grain could have traveled far.
- **Clay** – Mature; the main weathering product of silicates. Grain could have traveled far.
- **Magnetite and Feldspars** – Medium Maturity; withstands physical weathering long enough to be transported by rivers; will eventually weather. Grains could have traveled far.

- **Silicate minerals like olivine, pyroxene/amphibole, and micas**– Immature; weather quickly upon exposure. Grain could not have traveled far from source.
- **Rock fragments like basalt, serpentinite/chert, mudstone, and granite**– Immature; weather quickly upon exposure. Grain could not have traveled far from source.
- **Calcareous shells** – Immature; easily dissolved. Grain could not have traveled far from source.

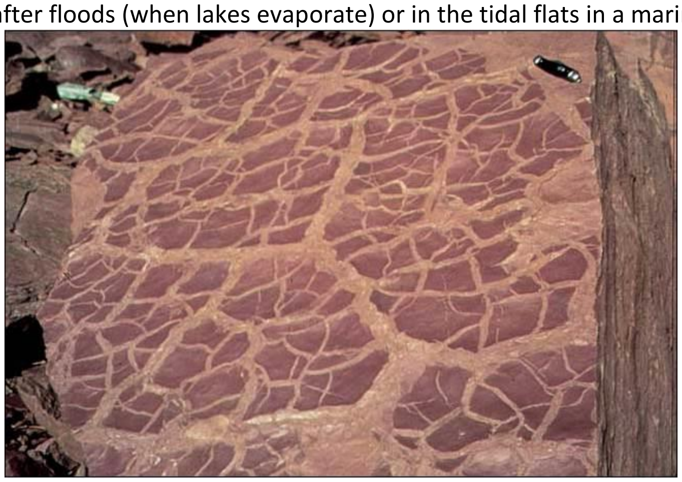
Sedimentary structures and environments

We use sedimentary rock structure and composition to learn something about the environment in which the rock formed (deposited or precipitated). There are many things about an **environment of deposition** that sedimentary rocks preserve and which give us clues about its formation. For example:

Fossilized Ripple Marks – Glacier National Park
Ripple marks indicated sediment formed where water moved regularly over it – ripples can be symmetrical as like the ones that form in the surf zone of a beach where water moves back and forth or asymmetrical along the bottom of a river where water only flows in one direction.

Oyster Fossil – Fossil Ridge – Mt. Diablo State Park
Fossils of clams indicate the sediment formed in a near-shore marine environment (in climate conditions conducive to clams). Fossils of Oak tree leaves suggest sediment formed inland, near an Oak forest (again in climate conditions conducive to Oak trees).

Mud cracks indicate sediment formed in an area where muds were deposited and the surface dried out, like in the desert after floods (when lakes evaporate) or in the tidal flats in a marine environment.



Fossilized Mud Cracks – Glacier National Park

Current Mud Cracks forming – Death Valley National Park – Marc Salomon

The most common sedimentary structure is layering or **stratification**. Sedimentary rocks form in horizontal layers or **beds**, because they come from accumulations of sediment or precipitation, both of which usually happen (thanks to gravity) along the horizontal. Contacts between different layers of sedimentary rock are called **bedding planes**. Sometimes sediment accumulates along an inclined surface, like sand along the slip-face of a sand dune. Such inclined deposits often change and shift as the wind changes. Sedimentary rocks that display this type of alternating inclined strata have **cross bedding**. Depositional environments that contain such deposits include sand dunes in the desert or those that exist behind a beach along the shoreline.

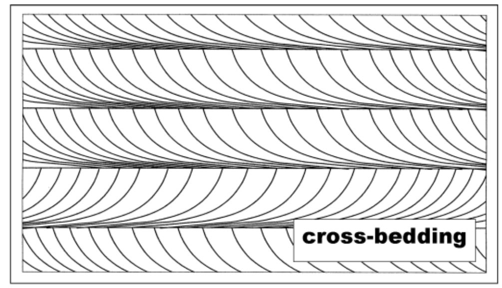


Image: Ralph Dawes and Cheryl Dawes – Creative Commons: CC BY 3.0 US

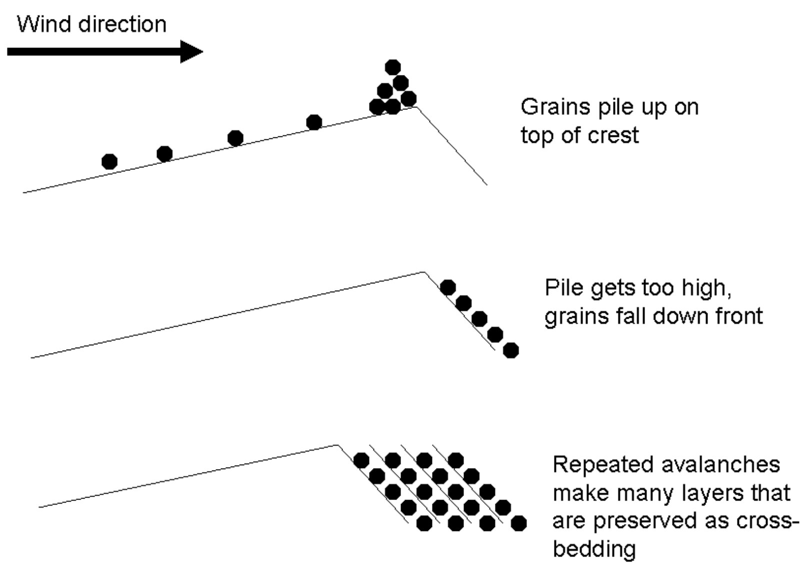
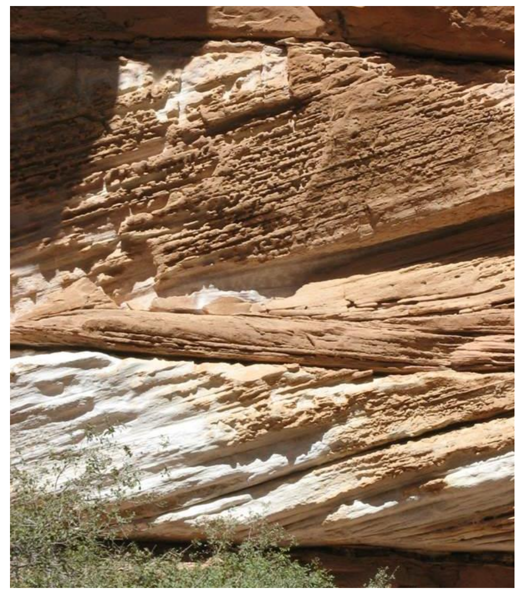


Image: Diane M. Burns – Creative Commons: CC BY-NC-SA 3.0



Fossilized Cross Beds
Grand Canyon National Park

We can use sorting in a single bed to determine whether the sediment accumulated gradually or quickly, was sorted by water or not at all, etc. **Graded bedding** is a single layer of sediment where the bottom of the layer contains the largest grains, and as you move higher in the layer, the grain sizes decrease. Such a feature forms only when high-energy water that is strong enough to carry all grain sizes suddenly drops its energy (or velocity) and quickly dumps its sediment load. The larger, heavier particles settle first – the smaller finer ones are last. Depositional environments that contain such deposits include the base of a submarine canyon (turbidity current deposits) or in river deposits, where flood waters drop their sediment load.

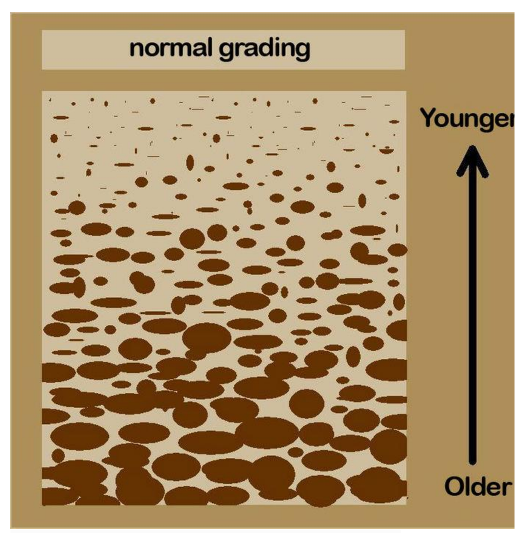


Image: Reinhard Kirchner – Creative Commons – CC BY-SA 3.0

Sedimentary Rock Characterization and Identification LAB

Chemical sedimentary rock (precipitated minerals or recrystallized shells – interlocking microscopic crystalline texture)

Composition	Texture and physical properties	Name	Depositional environment
Calcium carbonate $CaCO_3$	Interlocking texture, crystals too fine to see. Light brown, grey, or white.	**Limestone** (Dolostone if has Mg)	Precipitation in the deep sea or recrystallization of shells accumulated on the deep sea floor (clastic texture gone).
	Spherical grains like tiny beads (<2 mm) with concentric laminations.	Oolitic limestone	Precipitation in the surf zone near reefs, around fine sand grains, like pearls in oysters
	Layers of crystals – formed from evaporation of water.	Evaporitic or crystalline limestone	Precipitation in inland seas and other supersaturated bodies of water (like travertine deposits associated with hydrothermal springs)
Quartz (microcrystalline) or Silica (no crystals) SiO_2	Interlocking texture, crystals too fine to see. White, red, brown, black, or green.	Chert	Deep ocean floor –recrystallization of shells or buried sponges (or other organic detritus made from SiO_2)
	Black nodules, with powdery white rind.	**Flint** (nodular chert)	Deep ocean floor – nuggets of silica detritus (sponge spicules or shells) deposited in chalk layers (mostly calcite shell debris) and then recrystallizing as nodules.
Halite NaCl	Crystalline; salty taste	Rock salt	Precipitation in salt lakes and inland seas.
Gypsum $CaSO_4 \cdot 2H_2O$	Very soft, crystalline	Rock Gypsum	Precipitation in salt lakes and inland seas.

Clastic sedimentary rock (cemented or compacted clasts)

Organic (biochemical) sedimentary rock (clasts are mostly shells)

Grain sizes:
Gravel (>2mm); Sand (>1/16 mm; < 2 mm); Mud (<1/16) mm

Composition and Texture	Grain size	Name	Depositional environment
Calcium carbonate $CaCO_3$ WHITE (usually); Macro/microscopic shell fragments; Loosely cemented; porous.	Gravel	**Coquina** (limestone)	Beach with fringing reef
	Sand	**Calcarenite** (limestone)	At outside edges of fringing reefs
	Mud	**Chalk** (limestone)	Deep seafloor where plankton with microscopic $CaCO_3$ shells rain down.
Silica SiO_2 WHITE (usually); Macro/microscopic shell fragments. Loosely cemented; porous.	Mud	Diatomite (chert)	Deep seafloor where plankton with microscopic SiO_2 shells rain down.

Detrital sedimentary rock (clasts are mostly rock and/or mineral fragments

Grain size	Texture and composition	Name	Depositional environment
Gravel	Rounded fragments; poorly sorted	Conglomerate	Beach headlands, natural levees, tops of alluvial fans.
> 2 mm	Angular fragments; poorly sorted	Breccia	Base of landslides, faults, and debris flows.
Sand	Mostly quartz grains; well sorted; well rounded	Quartz sandstone	Beach, sand dunes (desert or beach); river banks. Source rock probably far away.
< 2 mm	>25% potassium feldspar grains, with quartz	Arkose	Beach sands; river deposits. Source rock most likely feldspar-rich granite.
> 1/16 mm	Mixed mineral grains/rock fragments.	Graywacke	River deposits or beach sands where source rock is nearby.
Mud < 1/16 mm	Microscopic quartz/clay grains; can be bedded. Shale variety is compact; splits into thin layers	Mudstone or Shale	Shallow, quiet lagoon; tide flats; outer continental shelf; deep sea.

Sedimentary Rocks Prereading Homework

1. Through what three primary ways can sedimentary rocks form?
2. What are the three main categories of sedimentary rock?
3. Which silicate mineral is least likely to weather and so common in mature beach sands?
4. Which mineral is the most common chemical weathering product of silicates and so common in mature sediment?
5. What does *clastic* mean?
6. What grain size is the largest (>2mm)?
7. What grain size is the smallest (<1/16 mm)?
8. What grain size is in the middle (1/16 to 2 mm)?
9. Explain what the possible depositional environment and history might be for a series of sedimentary rock layers that contain *cross bedding*. (Specific geologic environments.)
10. Explain what the possible depositional environment and history might be for a series of sedimentary rock layers that contain *graded bedding* – largest grains at bottom of layer – getting smaller as you move up into the layer. (Specific geologic environments.)
11. Which sedimentary rock consists of tiny spherical beads of calcium carbonate?
12. Which sedimentary rock consists of unsorted, angular detrital clasts of all grain sizes?
13. Which sedimentary rock consists of mud-sized calcareous shells deposited on the seafloor (porous and white)?
14. What do we call sandstones consisting primarily of K-feldspar?

Sedimentary Rocks Lab Exercises

1. For Box A: Instructions -- *(*NOTE: If grains are mud-sized or fine sands, no need to provide composition or grain shape because you can't see them!*)*
   Composition: Describe the composition of any grains you can see (use hand lens for hand samples and ZOOM tool for images). Use percentage guideline sheets in appendix to help approximate the percentage of each component. Example: quartz >75%, rock fragments ~20%, shells 5%.
   Grain size and shape: For grain size and shape, **circle all correct choices**. Underline the most dominant one. Review prereading for trait definitions. Use appendix guide for size dimensions.
   Sorting: Get answer solely from size data. Review prereading for trait definitions.
   Special textures: For nonshaded boxes only, describe special textures that are present in the various rocks. (Examples: mud cracks, fossils, ripple marks, cross-bedding, graded bedding, layering, etc.) If fossils exist, identify the organism and use it to help determine depositional environment.
   Maturity and Depositional environment: Based on all the above factors, interpret the sediment's maturity and depositional environment. (Not all factors will indicate same level of maturity. Use your best judgment.)

Sample #	Grain composition & approx. %	Grain shape	Grain size	Grain sorting	Special textures	Maturity	Depositional environment
1		Angular Subangular Subrounded Rounded Well rounded	Gravel (>2 mm) Coarse sand Medium sand Fine sand Mud (<1/16 mm)	Very poorly sorted Poorly sorted Moderately sorted Well sorted Very well sorted		Immature Intermediate Mature	
60		Angular Subangular Subrounded Rounded Well rounded	Gravel (>2 mm) Coarse sand Medium sand Fine sand Mud (<1/16 mm)	Very poorly sorted Poorly sorted Moderately sorted Well sorted Very well sorted		Immature Intermediate Mature	
6031		Angular Subangular Subrounded Rounded Well rounded	Gravel (>2 mm) Coarse sand Medium sand Fine sand Mud (<1/16 mm)	Very poorly sorted Poorly sorted Moderately sorted Well sorted Very well sorted		Immature Intermediate Mature	
6037		Angular Subangular Subrounded Rounded Well rounded	Gravel (>2 mm) Coarse sand Medium sand Fine sand Mud (<1/16 mm)	Very poorly sorted Poorly sorted Moderately sorted Well sorted Very well sorted		Immature Intermediate Mature	

Sample #	Grain composition & approx. %	Grain shape	Grain size	Grain sorting	Special textures	Maturity	Depositional environment
6042		Angular Subangular Subrounded Rounded Well rounded	Gravel (>2 mm) Coarse sand Medium sand Fine sand Mud (<1/16 mm)	Very poorly sorted Poorly sorted Moderately sorted Well sorted Very well sorted		Immature Intermediate Mature	
6033		Angular Subangular Subrounded Rounded Well rounded	Gravel (>2 mm) Coarse sand Medium sand Fine sand Mud (<1/16 mm)	Very poorly sorted Poorly sorted Moderately sorted Well sorted Very well sorted		Immature Intermediate Mature	
A1		Angular Subangular Subrounded Rounded Well rounded	Gravel (>2 mm) Coarse sand Medium sand Fine sand Mud (<1/16 mm)	Very poorly sorted Poorly sorted Moderately sorted Well sorted Very well sorted		Immature Intermediate Mature	

2. For Box B, separate the samples into groups: chemical, clastic detrital, and clastic shells. (7 samples total)

Chemical	Clastic Detrital	Clastic shells

3. For Box C, correctly identify each sample. Describe the most diagnostic/distinguishing characteristics of that rock (the sample that you are observing). Make them unique! If any description can apply to more than one rock type, you haven't found the right description!

Use this checklist to help and record diagnostic properties.

□ Chemical texture

  □ Reacts to acid ($CaCO_3$); □ Doesn't react (SiO_2); □ Doesn't react; (salt); □ Doesn't react (gypsum)

  □ Clastic texture, but clasts are all beads that react to acid ($CaCO_3$)

□ Clastic texture, clasts appear to be visible shells or white mud

  □ Gravel-sized shells; □ sand-sized shells;

  □ mud-sized shells that react with acid;

  □ mud-sized shells that don't react]

□ Clastic texture, clasts appear to be detrital

  □ Gravel-sized rounded clasts; □ Gravel-sized angular clasts;

  □ sand-sized clasts

    □ mostly quartz; □ lots of Potassium Feldspar; □ mostly rock gragments

  □ mud-sized clasts homogeneous □ mud-sized clasts, dense with planar fractures

Sample	Rock name	Diagnostic characteristics (include texture, grain size (if clastic), and composition)
1		
2		
3		
4		
5		
6		
7		
8		

Sample	Rock name	Diagnostic characteristics (include texture, grain size (if clastic), and composition)
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Observe and describe textures and composition of a provided sedimentary rock sample	A | B | C | D | F	
Identify and name sedimentary rocks by hand sample	A | B | C | D | F	
Compare and contrast textures, compositions, and special features within sedimentary rocks and what they indicate about the formation environment of the rock	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Sedimentary Rocks Practice Sheet

Go to the course website flashcards and videos (and come to lab itself) and practice identification of all the different minerals and rocks.
Be sure that for each rock and mineral, you know the environment in which it formed and its distinguishing characteristics.

NOTE: On the exam you will get a list of rock and mineral names, but there is no guarantee that you'll see every rock or mineral OR that you'll see a rock or mineral only once. However, you will NOT see a mixture of rock or mineral types. In other words, all sedimentary rocks will be together – and not mixed with igneous rocks.

Sedimentary rock name	**Texture, including grain size, if appropriate**	**Composition**	**Possible depositional environments**
Mudstone			
Shale			
Arkose			
Quartz sandstone			
Graywacke			
Breccia			
Conglomerate			
Flint			
Chert			
Evaporitic limestone			
Oolitic limestone			
Limestone			
Diatomite			
Chalk			
Calcarenite			
Coquina			

SEDIMENTARY ROCKS QUESTIONS

What are the three main categories of sedimentary rock?	
Which mineral is produced from chemical weathering of feldspar and will thus be present in mature sedimentary rocks?	
Which igneous mineral is resistant to chemical weathering and will thus be present in great abundance in mature sedimentary rocks?	

In what environment would ripple marks form?	
In what environment would cross bedding form?	
In what environment would mud cracks form?	
In what environment would graded bedding form?	
In what environment would a sand dollar fossil form?	

KEY

Sedimentary rock name	**Texture, including grain size, if appropriate**	**Composition**	**Possible depositional environments**
Mudstone	Detrital Clastic, mud-sized grains	Usually clay minerals (can see only with scope)	Lake, lagoon, deep ocean, outer continental shelf
Shale	Detrital Clastic, mud-sized grains, dense and splits in layers	Usually clay minerals (can see only with scope)	Lake, lagoon, deep ocean, outer continental shelf
Arkose	Detrital Clastic, sand-sized grains (may also contain mud sized)	A lot of K-feldspar (rest can be anything)	Sand dunes (desert or beach), river bars
Quartz sandstone	Detrital Clastic, sand-sized grains (may also contain mud sized)	Mostly quartz	Sand dunes (desert or beach), river bars
Graywacke	Detrital Clastic, sand-sized grains (may also contain mud sized)	Mostly rock fragments (some minerals)	Sand dunes (desert or beach), river bars
Breccia	Detrital Clastic, gravel-sized grains (may also contain sands and muds), grains are angular.	Mostly rock fragments (some minerals)	Base of landslides, faults, and debris flows.
Conglomerate	Detrital Clastic, gravel-sized grains (may also contain sands and muds), grains are rounded.	Mostly rock fragments (some minerals)	Beach headlands, natural levees, tops of alluvial fans
Flint	Chemical (surrounded by white rind)	Quartz (microscopic) (white rind is calcite)	Deep ocean floor –nuggets of silica detritus deposited in chalk layers (mostly calcite shell debris) and then recrystallizing as nodules.
Chert	Chemical	Quartz (microscopic)	Deep ocean floor – recrystallization of shells or buried sponges (or other organic detritus made from SiO_2)
Evaporitic limestone	Chemical, with layers of crystals	Calcite crystals (any size)	Precipitation in inland seas and other supersaturated bodies of water (like travertine deposits associated with hydrothermal springs)
Oolitic limestone	Chemical beads glued together	Calcite	Precipitation in the surf zone near reefs, around fine sand grains, like pearls in oysters

Sedimentary rock name	Texture, including grain size, if appropriate	Composition	Possible depositional environments
Limestone	Chemical	Calcite (microscopic)	Deep ocean floor – recrystallization of shells (or other organic detritus made from $CaCO_3$) OR recrystallized, compressed coral reefs (near shore)
Diatomite	Bioclastic, mud-sized grains	Glass (quartz) shells (microscopic)	Deep ocean floor – accumulation of shells (SiO_2)
Chalk	Bioclastic, mud-sized grains	Calcite shells (microscopic)	Deep ocean floor – accumulation of shells ($CaCO_3$)
Calcarenite	Bioclastic, sand-sized grains, (may also contain mud sized)	Calcite shells	At outside edge of coral reefs
Coquina	Bioclastic, gravel-sized grains (may also contain sands and muds	Calcite shells	Coral reefs (nearshore)

SEDIMENTARY ROCKS QUESTIONS

What are the three main categories of sedimentary rock?	Chemical, Organic clastic, Detrital clastic
Which mineral is produced from chemical weathering of feldspar and will thus be present in mature sedimentary rocks?	Clay
Which igneous mineral is resistant to chemical weathering and will thus be present in great abundance in mature sedimentary rocks?	Quartz
In what environment would ripple marks form?	Where there's current in the water – muddy or fine sandy bottoms below tidal currents or rivers.
In what environment would cross bedding form?	Sand dunes.
In what environment would mud cracks form?	Where mud is deposited and water covers it and then evaporates away – so tidal flats during the summer or lakes that dry up in the desert.
In what environment would graded bedding form?	Turbidity current deposits at the base of submarine canyons (or deposits after floods in the desert).
In what environment would a sand dollar fossil form?	Sandy-bottomed flat coastal region (off a beach)

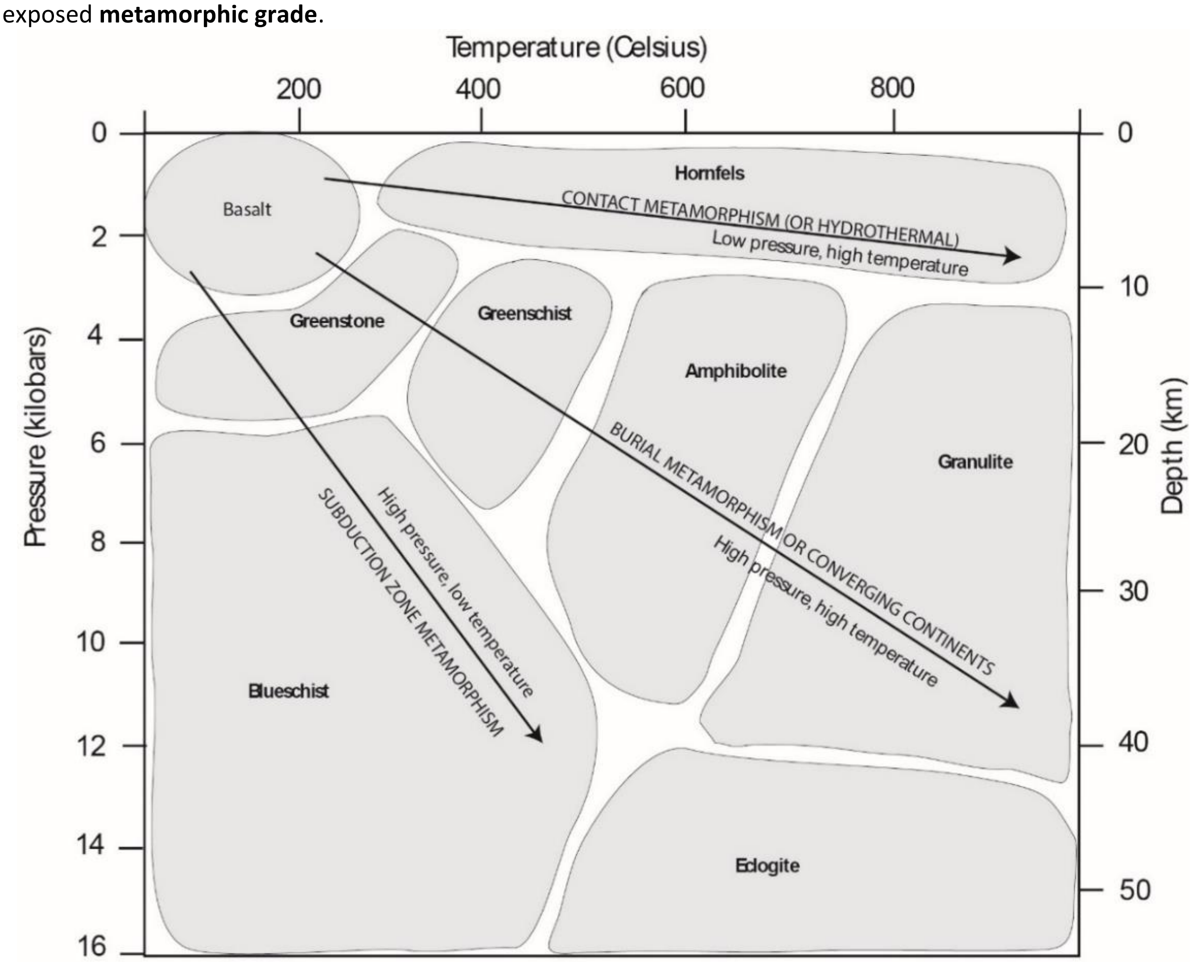
Metamorphic Rocks

Metamorphic rocks are igneous, sedimentary, or other metamorphic rocks that have undergone extreme change (without melting – remaining always solid). Such change results from pressure increase, temperature increase, and/or injection of hydrothermal, chemically active fluids. Metamorphism occurs generally between 200°C and 800°C. Lower temperatures are associated with sedimentary processes; higher temperatures would melt the rock, turning it into an igneous rock.

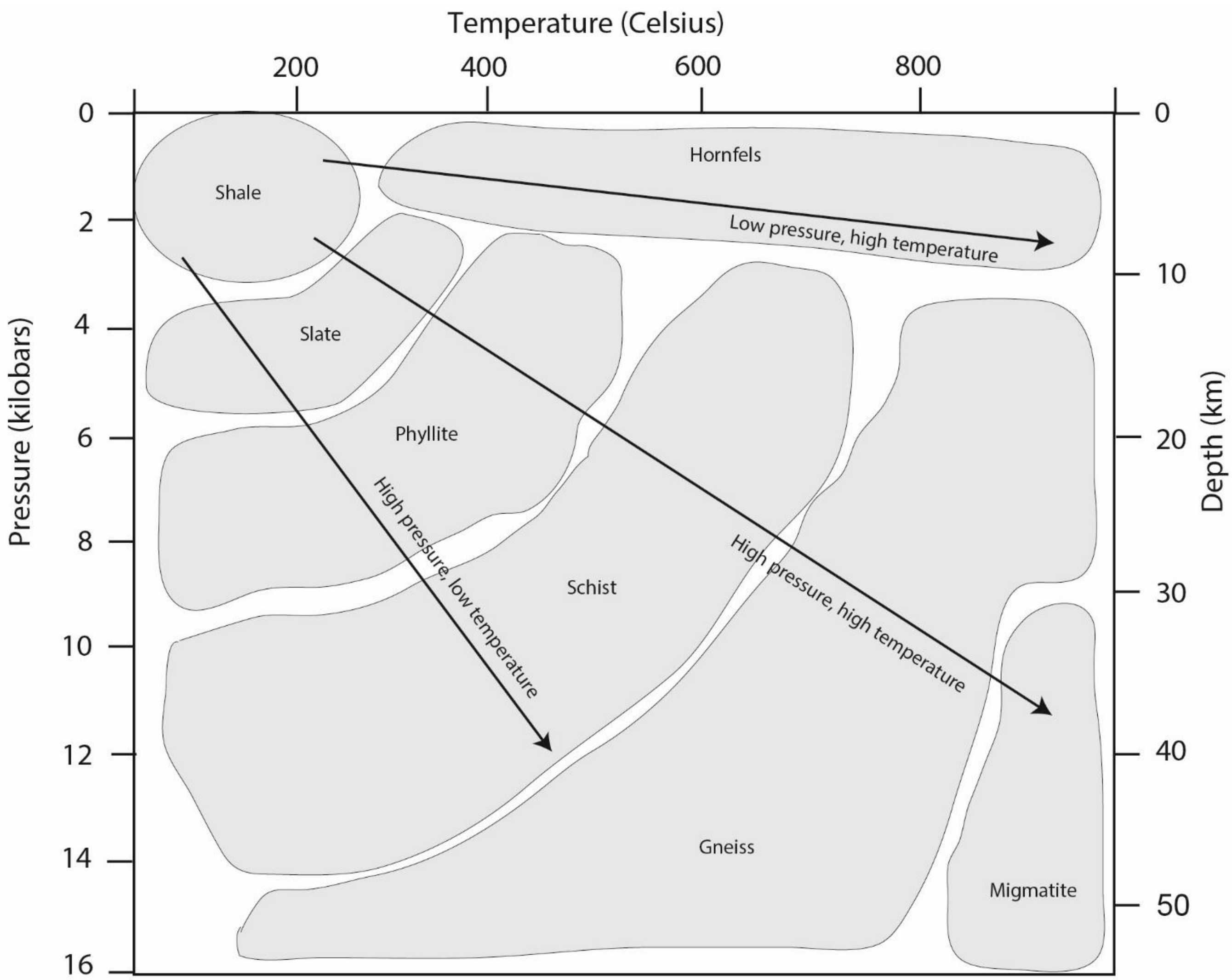
Common metamorphic settings for metamorphism and their characteristics and symbol

Metamorphic setting		Pressure (P)	Temperature (T)	Chemically active fluids
Contact metamorphism	C	Low	High: increasing toward magma	High – from magma and from heated surface waters.
Burial metamorphism	B	High: steadily increasing with depth	Low to High: steadily increasing with depth	Low – liberated from hydrous minerals
Converging continents (regional)	R	High: increasing with depth	Low to High: steadily increasing with depth	Low – liberated from hydrous minerals
Subduction zone metamorphism	S	High	Low to medium: slowly increasing with depth	High – from hydrous minerals in hydrothermally altered ocean sediments and basalts; and from water trapped in pores and cracks.
Hydrothermal circulation at spreading centers	H	Low	High because occurs at the mantle/crust boundary.	High – from magmas and from circulating seawater

We use mineralogy and texture in a metamorphic rock to determine the agents that caused the rock to form (the highest temperature and pressure and/or types of fluids to which a rock was exposed). We call the intensity of metamorphism to which a rock was exposed **metamorphic grade**.



GRAPHIC OF BASALT METAMORPHISM BY METAMORPHIC SETTING


Temperature (Celsius)
200
400
600
800
Pressure (kilobars)
0
2
4
6
8
10
12
14
16
Depth (km)
0
10
20
30
40
50
Shale
Hornfels
Slate
Phyllite
Schist
Gneiss
Migmatite
Low pressure, high temperature
High pressure, low temperature
High pressure, high temperature

Textural changes

Major textural changes occur as metamorphic grade increases, due to increased pressures and temperatures. If the pressures are uniform in all direction (**confining pressure**), the results are different than if the pressure is high in only one direction (**directed pressure**). In the latter case, pressure is released if minerals align themselves perpendicular to the direction of pressure.

- **Density increases (volume shrinks)** – Grains/crystals pack closer together under confining pressure.
- **Foliation increases** – Minerals align when under directed pressure.
- **Crystal size increases** – Grain boundaries migrate, enlarging crystal size as pressure (any kind) placed on crystal boundaries.

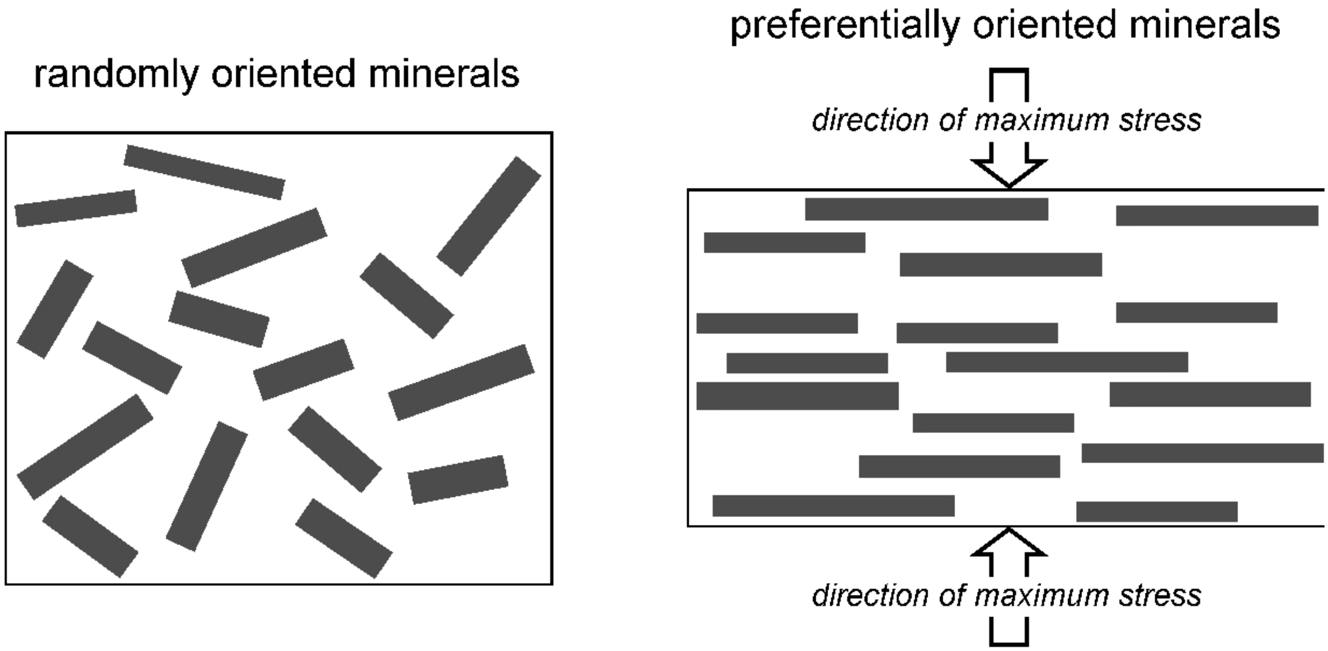
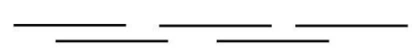
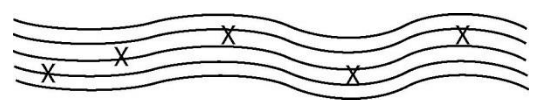
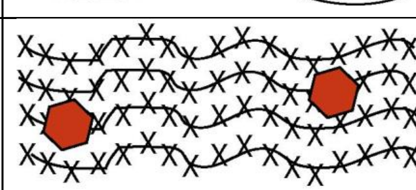
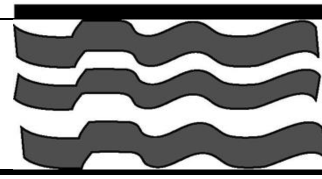


Image: Ralph Dawes and Cheryl Dawes – Creative Commons: CC BY 3.0 US

Other Textural Changes found in metamorphic rocks:

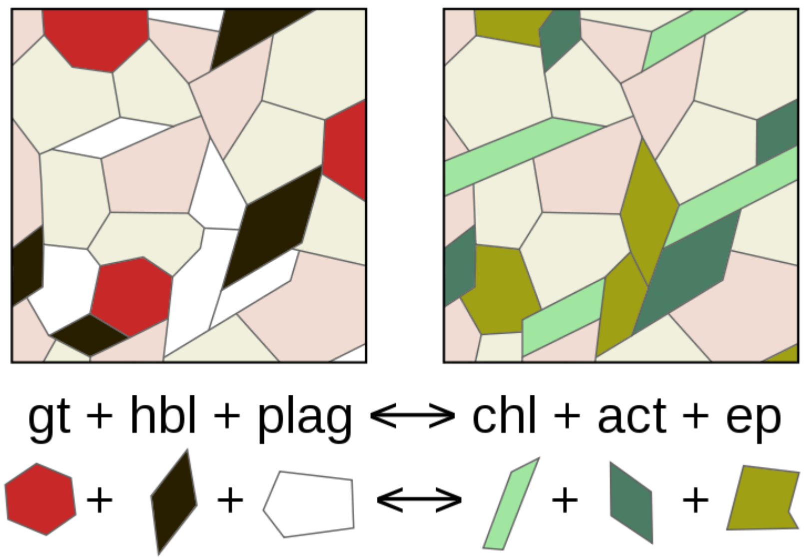
- **Veins** – Fractures filled by minerals that precipitated from hydrothermal fluids.
- **Porphyroblasts** – Unusually large crystals set in a finer-grained groundmass.
- **Folds, lineations, stretched or sheared grains** – Clasts or layers in the original rock are stretched out or folded under directed pressure.
- **Slickensides** – Smoothed, grooved surfaces – formed when two rocks move across one another, like along faults or cracks or rocks in glaciers moving across bedrock.

Grade	Foliation type	Description	Picture
Low	Rock or slaty cleavage	Microscopic, aligned mica minerals. Planar cleavage. No visible minerals. Dense.	
Low to med	Phyllitic texture	Mostly microscopic, aligned mica minerals. Only a few visible, isolated minerals peeking out of satiny background. Foliation is undulating.	
Med to high	Schistosity	Mostly visible biotite minerals – all aligned, giving rock a scaly look, like a fish. Foliation is undulating and fine. Some large porphyroblasts may peek out.	

Grade	Foliation type	Description	Picture
High	Gneissic texture	All visible, interlocking crystals, separated into alternating dark- and light-colored layers.	
Very high	Migmatitic texture	Gneissic texture where ½ melted, and the high temperatures caused folding of the layers.	

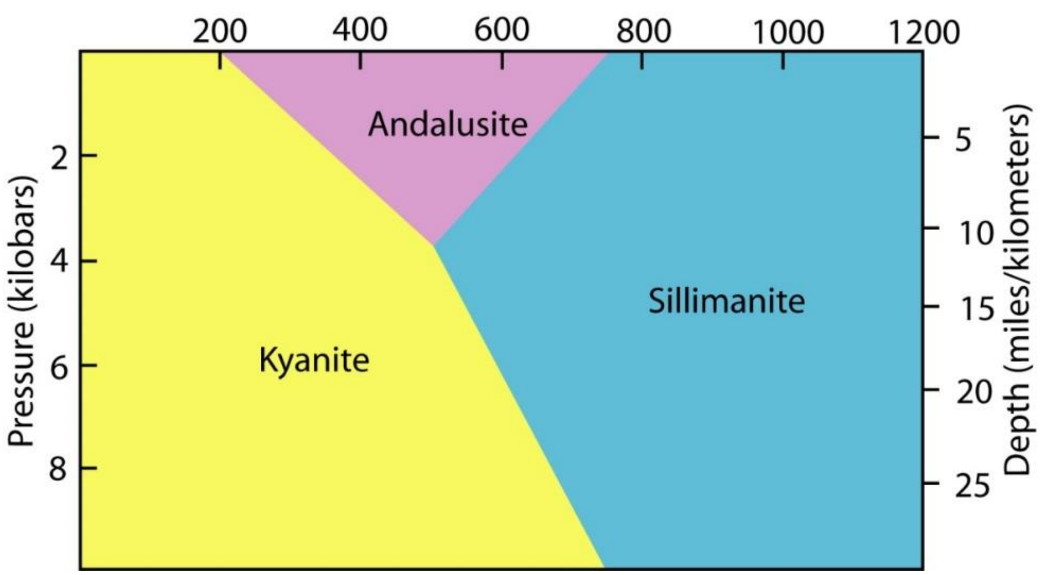
Mineral changes

Minerals can change and grow in metamorphic rocks, without melting. The chemically active fluids and pressure at crystal grain boundaries can cause the ions in the solid rock to migrate as though they were in a fluid. For this reason, metamorphic minerals tend to show some of the most perfect crystal faces. In addition, as metamorphic grade increases, **minerals change to more stable ones** and **crystals get larger**.



Simplified schematic representation of a metamorphic chemical reaction. Boxes represent the whole rock mineralogy. In this example the reaction is complete: no relict minerals remain. The reaction in question will in nature take place when a rock goes from amphibolite to greenschist facies. Abbreviations of minerals: act = actinolite; chl = chlorite; ep = epidote; gt = garnet; hbl = hornblende; plag = plagioclase. Two non-participating minerals are present in the rocks: these could be (for example) K-feldspar and quartz. Image: Woudloper – Creative Commons – CC BY-SA 3.0

Polymorph example: These three minerals have the same chemical formula (Al_2SiO_5), but are stable at different pressure and temperature conditions. During metamorphism, they can change from one form to another to reach stability at new temperatures and pressures.



Mineral Stability with increasing grade during subduction zone metamorphism
(pressure and temperature both rise, but temperature less so than pressure).

<table>
<tr><td>Parent Rock</td><td>Low Grade</td><td>Medium Grade</td><td>High Grade</td></tr>
<tr><td>Mafic Igneous Rock</td><td colspan="3">Rocks:
|---Greenstone---------------|------------Blueschist-----------------|---------Eclogite--------------------|
Minerals
|----CHLORITE------------------------------|
|----ACTINOLITE--------------------------|
|-----------------EPIDOTE--------------|
|-------GLAUCOPHANE-------|
|----------LAWSONITE----------|
|--BIOTITE---|
|---------------------OMPHACITE-----------------------------|
|---------------------GARNET-----------------------------------|
|-------------------KYANITE--------------------------|
|---QUARTZ---|</td></tr>
</table>

Mineral Stability with increasing grade during regional metamorphism *(pressure and temperature both rise).*

<table>
<tr><td>Parent Rock</td><td>Low Grade</td><td>Medium Grade</td><td>High Grade</td></tr>
<tr><td>Mafic Igneous Rock</td><td colspan="3">Rocks:
|---Greenstone--|---Greenschist-------|-----Amphibolite-------|--------Granulite-------------------|
Minerals:
|----CHLORITE------------------------------|
|-----------------EPIDOTE--------------|
|---------------------HORNBLENDE----------------------|
|---------------------GARNET----------------|
|-----------------PYROXENE-------------|</td></tr>
<tr><td>Mudstone/Shale</td><td colspan="3">Rocks:
|---Slate----|---Phyllite-----|-----Schist------------------|--------Gneiss------|----Migmatite----------|
Minerals:
|----CHLORITE--------------|
|---MUSCOVITE--------------|
|---BIOTITE--|
|----------------GARNET---|
|----STAUROLITE--|
|-KYANITE-|
|---------SILLIMANITE-----------|
|---QUARTZ---|
|--FELDSPAR---|</td></tr>
</table>

Mineral Stability with increasing grade during all types of metamorphism

<table>
<tr><td>Parent Rock</td><td>Low Grade</td><td>Medium Grade</td><td>High Grade</td></tr>
<tr><td>Sandy limestone</td><td colspan="3">Rocks:
|---Quartzite---|
|---Marble--|
Minerals:
|---QUARTZ--|
|--CALCITE--|</td></tr>
</table>

Metamorphic rock names based on parent rock, geologic setting, and metamorphic grade.

Metamorphic settings	**B, R, S**	**B, R, S**	**S**	**S**	**BR**	**B, R, S**	**B, R, S**
Parent rock	**Shale**	**Granite**	**Serpent-inite**	**Basalt**	**Basalt**	**Chert (SiO_2)**	**Limestone ($CaCO_3$)**
GRADE:						Quartzite* (crystals grow larger)	Marble* (crystals grow larger)
Low	Slate			Greenstone	Greenstone		
Low - Med	Phyllite			Blueschist	Greenschist		
Med - High	Schist				Amphibolite		
High	Gneiss	Gneiss		Eclogite	Granulite		
Very High	Migmatite	Migmatite	Soapstone				

Metamorphic settings	**C**	**C**	**C**	**C**	**C**	**H**
Parent rock	**Chert (SiO_2)**	**Limestone ($CaCO_3$)**	**Mixture of minerals**	**Shale**	**Basalt**	**Mantle rock (Peridotite)**
GRADE:	Quartzite* (crystals grow larger)	Marble* (crystals grow larger)	Skarn* (crystals grow larger; form new minerals)	Hornfels* (crystals grow larger)		
Low						
Low - Med						
Med - High						Serpentinite
High					Hornfels	
Very High						

*Quartzite, Marble, Skarn, and shale-metamorphosed Hornfels exist through all grades. The only way to tell grade of these rocks is through crystal size and in the case of skarn, mineral composition.

Metamorphic Rock Characterization and Identification – LAB

Texture	Name	Parent rock	Geologic settings	Grade	Description
Foliated	Slate	Shale	B, R, S	Low	Dull; similar to shale, but more dense and breaks into hard flat sheets. No visible crystals.
	Phyllite	Shale	B, R, S	Low-med	Similar to slate, but sheets are undulating (wrinkled). Luster is more silky or satiny than slate. Some isolated crystals might be visible.
	Schist	Basalt/gabbro, shale	B, R, S	Med-high	Crystals easily visible throughout rock – usually all micas, giving it a scaly look. Foliation greater than phyllite. Minerals can be garnet + biotite + chlorite + muscovite + quartz + plagioclase + epidote + kyanite. Chlorite disappears and kyanite appears as grade increases.
	Blueschists contain a blue amphibole (glaucophane) + blue silicate similar to epidote (lawsonite) or epidote. Formed through medium grade subduction of basalt/gabbro. **Greenschists** contain green minerals (actinolite + epidote + albite +/- chlorite +/- quartz) giving it a green appearance. Formed through medium grade burial of basalt/gabbro.				
	Gneiss	Granite/rhyolite, shale	B, R, S	High	Grains medium to coarse; light and dark minerals segregated into bands. Gneissic texture.
	Migmatite	Gneiss	B, R, S	Very high	Contorted layers: gneissic texture that has been folded: some of the layers/bands have melted and crystallized as granite.
Weakly foliated	Greenstone	Basalt/gabbro	B, R, S	Low	Very fine grained (too small to see crystals); light to yellow green (from chlorite, epidote, and/or actinolite).
	Eclogite	Basalt/gabbro	S	High	Red garnets scattered uniformly throughout a finer-grained green groundmass (bright-green pyroxene: omphacite). May have quartz, kyanite, or biotite.
	Serpentinite	Peridotite	H	Med-high	Green, mottled, massive. Smooth, rounded slippery surfaces. Can be black or reddish. Usually displays slickensides
	Soapstone	Serpentinite	S	High	White to green. Very soft. Soapy feel. Primary mineral is talc: can be scratched with fingernail.
Non foliated	Hornfels	Basalt/gabbro, mudstone	C	All*	Sugary or microcrystalline, usually dark-colored. *If clearly formerly basalt, grade must be high.
	Marble ($CaCO_3$)	Pure limestone (only $CaCO_3$)	B, R, S, C	All	Sugary, sandy, or crystalline; calcite or dolomite (form of calcite with Mg) crystals fused together. White to pink. Might have dark streaks.
	Quartzite (SiO_2)	Chert (only SiO_2) Quartz Sandstone	B, R, S, C	All	Sugary, sandy, or crystalline; can sometimes see quartz sand grains fused together; grains won't rub off like sandstone.
	Skarn	Impure limestone or chert, arkose, greywacke…	C	All	Crystalline; usually with large crystals, including calcite, quartz, garnet, epidote, pyroxene and other crystals, like sulfides.

*Remember: use mineral ID skills to help distinguish among some of these!

Metamorphic Rocks Prereading Homework

1. Which of these minerals gives no indication of metamorphic grade? a. Quartz b. Chlorite c. Hornblende d. Muscovite	2. Which of these minerals could NOT be formed in a low-grade metamorphic rock? a. Calcite b. Chlorite c. Muscovite d. Garnet
3. Which of these minerals indicates a low-grade metamorphic rock? a. Quartz b. Epidote c. Hornblende d. Kyanite	4. What does limestone metamorphose into under all conditions? a. Amphibolite b. Marble c. Eclogite d. Gneiss
5. What does mudstone or basalt metamorphose into in contact metamorphism? a. Hornfels b. Marble c. Quartzite d. Gneiss	6. Which of these rocks indicates highest grade of metamorphism? a. Migmatite b. Phyllite c. Slate d. Greenstone
7. What does mudstone become during regional or subduction zone metamorphism? (List the results in order from lowest grade – left – to highest grade – right).	
8. What are the pressure, temperature, and fluid conditions associated with subduction zones?	
9. What are the pressure, temperature, and fluid conditions associated with deep burial?	
10. What are the pressure, temperature, and fluid conditions associated with contact metamorphism?	
11. What happens to mineral size in quartzite as metamorphic grade increases?	

Metamorphic Rocks Lab Exercises

1. For Box A, name any minerals that you can identify. Estimate % and size (use ruler). Describe texture (type of foliation if any exists) including any special textures such as porphyroblasts, stretched pebbles, joints, veins, and slickensides. See prereading for more information.) Based on texture and mineralogy, estimate metamorphic grade and setting (identifying rock name might help.) Be sure to look at the provided sample of Andalusite – one of these rocks contains it! *(*For grade of nonfoliated rocks, use mineral type and size to estimate correct grade of specific sample.)*

Sample #	**Minerals and approx % (if visible)**	**Mineral size (range)**	**Texture (indicate level of foliation if exists AND special textures as described above)**	**Grade (*See note above!)**	**Metamorphic setting**
8042					
8120					
50-2					
B-1					
B-2					
8000					
8060					

Sample #	Minerals and approx % (if visible)	Mineral size (range)	Texture (indicate level of foliation if exists AND special textures as described above)	Grade (*See note above!)	Metamorphic setting
A2					
10					
C2					

2. For Box B, correctly identify each sample. Describe the most diagnostic/distinguishing characteristics of that rock (the sample that you are observing). Make them unique! If any description can apply to more than one rock type, you haven't found the right description!

Use this checklist to help and record diagnostic properties.

□ Nonfoliated texture; Homogenous color (all black or all white or all grey; some swirling colors okay, but all one mineral!)

□ Reacts to acid ($CaCO_3$); □ Doesn't react and is light colored (SiO_2); □ Doesn't react, but is dark colored

□ Weakly foliated texture;

□ Fine-grained light green or yellow; rough; □ Green groundmass with red garnets +/- kyanite; □ Mottled green, smooth, rounded homogenous, soft

□ Foliated texture

□ Slaty cleavage; □ Phyllitic texture; □ Gneissic texture; □ Migmatitic texture

□ Schistose texture with mostly actinolite minerals; □ Schistose texture with mostly blue minerals; □ Schistose texture with mostly micas

(*For grade of nonfoliated rocks, use mineral type and size to estimate correct grade of specific sample.)

Sample	Rock name	Parent rock	Met. Setting	Grade (*See note above!)	Diagnostic characteristics (foliation type and composition)
1					
2					
3					

Sample	Rock name	Parent rock	Met. Setting	Grade (*See note above!)	Diagnostic characteristics (foliation type and composition)
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
End table sample					

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Observe and describe textures and composition of a provided metamorphic rock sample	A | B | C | D | F	
Identify and name metamorphic rocks by hand sample	A | B | C | D | F	
Compare and contrast textures and minerals within metamorphic rocks and what they indicate about the formation environment of the rock	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Metamorphic Rocks Practice Sheet

Go to the course website flashcards and videos (and come to lab itself) and practice identification of all the different minerals and rocks,
Be sure that for each rock and mineral, you know the environment in which it formed and its distinguishing characteristics.

NOTE: On the exam you will get a list of rock and mineral names, but there is no guarantee that you'll see every rock or mineral OR that you'll see a rock or mineral only once. However, you will NOT see a mixture of rock or mineral types. In other words, all sedimentary rocks will be together – and not mixed with igneous rocks.

Metamorphic rock name	**Foliation**	**Distinguishing characteristics (textural and compositional as appropriate)**	**Parent Rock**	**Metamorphic Setting (BRSC okay)**	**Metamorphic Grade**
Eclogite					
Gneiss					
Greenstone					
Hornfels					
Marble					
Migmatite					
Phyllite					
Quartzite					
Schist					
Greenschist					
Blueschist					
Serpentinite					
Skarn					
Slate					
Soapstone					

METAMORPHIC ROCKS QUESTIONS

Which minerals are good indicators of low grades of metamorphism?	
Which minerals are good indicators of high grades of metamorphism?	
Which minerals give NO indication of metamorphic grade?	
What is the sequence of mudstone metamorphism in a subduction zone (from lowest to highest grade)?	

What is the sequence of basalt metamorphism in a subduction zone (from lowest to highest grade)?	
What do all calcite-bearing rocks become under metamorphosis? (Under all circumstances.)	
What do all silica-bearing rocks become under metamorphosis? (Under all circumstances.)	
What are some of the textural changes that occur as metamorphic grade increases?	

KEY

Metamorphic rock name	**Foliation**	**Distinguishing characteristics (textural and compositional as appropriate)**	**Parent Rock**	**Metamorphic Setting (BRSC okay)**	**Metamorphic Grade**
Eclogite	Weak	Green background mineral with small garnets spread throughout (may have kyanite).	Basalt	S	High
Gneiss	Gneissic – high	Planar dark and light (alternating) bands	Mudstone or granite	BRS	High
Greenstone	Weak to none	Green or yellow-green fine-grained groundmass	Basalt	BRS	Low
Hornfels	None	Sugary or microcrystalline	Basalt or mudstone	C	Low to High
Marble	None	Sugary or microcrystalline, dark colored	Limestones of all varieties	BRSC	Low to High
Migmatite	Very high	Contorted banding (light colored bands may look like granite)	Gneiss	BRS	Very High
Phyllite	Phyllitic	Undulating, satiny foliation, perhaps with a few isolated larger crystals peeking out	Mudstone	BRS	Low-Med
Quartzite	None	Sugary or microcrystalline, mostly quartz (might even see remnants of quartz grains)	Cherts of all varieties and Quartz SS	BRSC	Low to High
Schist	Schistose – High	Almost entirely large biotite grains, like scales; perhaps with a few isolated larger crystals peeking out like garnet.	Mudstone	BRSC	Medium to high
Greenschist	Schistose – High	Almost entirely green minerals like actinolite, foliated	Basalt	BR	Medium to high
Blueschist	Schistose – High	Almost entirely blue minerals like pyroxenes, foliated	Basalt	S	Medium to high
Serpentinite	Weak to none	Close to 100% serpentine – smooth, rounded masses	Peridotite (mantle rock)	H	Med to High
Skarn	None	Large grains of quartz, calcite, and other minerals, which can include garnet, hornblende, etc.	Arkose, Conglomerate, Breccia (mix)	C	Low to High
Slate	Slaty cleavage	Dull, similar to shale, but denser and breaks into hard flat sheets. No visible crystals.	Mudstone/shale	BRS	Low
Soapstone	Weak to none	100% talc in smooth, rounded masses.	Serpentinite	S	High

METAMORPHIC ROCKS QUESTIONS

Which minerals are good indicators of low grades of metamorphism?	The answers to this question depends on whether low grade is defined relative to temperature or pressure or both. Chlorite is the best for all settings, with Actinolite and Epidote as possible additions in the low-medium grade.
Which minerals are good indicators of high grades of metamorphism?	Garnet, Pyroxene, Kyanite
Which minerals give NO indication of metamorphic grade?	Calcite, Feldspar, Quartz
What is the sequence of mudstone metamorphism in a subduction zone (from lowest to highest grade)?	Slate, Phyllite, Schist, Gneiss, Migmatite
What is the sequence of basalt metamorphism in a subduction zone (from lowest to highest grade)?	Greenstone, blueschist, eclogite
What do all calcite-bearing rocks become under metamorphosis? (Under all circumstances.)	Marble
What do all silica-bearing rocks become under metamorphosis? (Under all circumstances.)	Quartzite
What are some of the textural changes that occur as metamorphic grade increases?	Crystal size increases, foliation increases, density increases, stretching of grains increases

Rock and Minerals Review Lab PREREADING

Some of these questions are inspired by work done in EER2020 “Creating Inquiry Labs” Workshop, August 2020 with Authors: Christopher Berg, Becky Jirón, Alexandra Priewisch, Katryn Wiese

PREPARATION:

- Gather five objects from around your house of roughly similar volume, but made of very different material AND ALSO OKAY TO SCRATCH THE SURFACE OF (so avoid anything precious). Examples: old plastic bottle, glass bottle, penny, iron nail, soap. You will use these to complete the prereading, but also be sure to save and bring for in-class lab discussion.
- Locate three different rocks from your environment (backyard, local park, wherever). Note where you found it and bring with you to class for in-class lab discussion.

At Home Materials -- Hardness *(~10-15 minutes)*

1. Set your 5 samples down alongside each other on a table and order them from softest to hardest -- remember hardness scale and what it means when one object scratches another.
2. Record results below and reflect and write a paragraph describing how accurate you think your results were and why. What methods did you use to assess hardness? What was useful? What wasn’t?

Materials listed in order from softest to hardest:	**Reflection on accuracy. What methods did you use to assess hardness? What was useful? What wasn’t?**
1. Softest 2. 3. 4. 5. Hardest	

3. Watch the **instructor’s video** (on website – Hardness only!) of completing the same procedure. After reviewing the video, what additional information/insights do you have?

4. TAKE A PHOTO OF YOUR MATERIALS AND COMBINE WITH PREREADING FOR UPLOAD PDF.

At Home Materials -- Density *(~10-15 minutes)*

1. Using the same five samples, order them from least dense to most dense.

2. Record results below and reflect and write a paragraph describing how accurate you think your results were and why. What methods did you use to assess density? What was useful? What wasn't? How well were you able to distinguish between density and mass?

Materials listed in order from least dense to most dense:	**Reflection on accuracy. What was useful? What worked well? What was most challenging? How well were you able to distinguish between density and mass?**
Least dense 1. 2. 3. 4. 5. Most dense	

3. Watch the **instructor's video** (on website -- Density) of completing the same procedure. After reviewing the video, what additional information/insights do you have?

At Home Materials -- Material Properties *(~5 minutes)*

What other properties of these materials do you observe that might be useful for identifying each of these materials in a different sample and why? Be as specific as you can. Record notes below.

LAB: What kind of rock am I? *(30 minutes)*

In groups of 3, you will be collectively reviewing the 3 rocks you brought to class from your neighborhood. For each one:

1) Take a photo of each rock and add it to the **Rock Show and Tell photo album (link on website)**.
    a) Click on photo in album and then click on (i) to add information about the photo

b) Enter a description of the rock (NOT the name of the rock) that starts with the **location where it was gathered.** Example: Ocean Beach – sand-size grey-colored grains with a fossil sand dollar.

2) Complete the table below:

a) Identify the rock type: Igneous, Sedimentary, or Metamorphic and if possible the name

b) Detail the evidence that led you in your group to pick the correct rock type

Rock ID	**Rock type and name (if possible)**	**Evidence**

Challenges and Successes

What were some of the challenges you faced in classifying a rock gathered from your neighborhood?

Rock and Mineral Descriptions -- how good are yours? *(5-10 minutes)*

[Album of above minerals (3 different views)]

Pick one of the above minerals and provide below a description of it that you think others could use to effectively choose this mineral from the pile (and also distinguish it if another sample appeared that didn't look identical to this one).

Matching question: 5 different mineral samples and 5 descriptions of this mineral written by students from previous semesters (for different samples than the ones shown).

1. This mineral is kind of greenish and lumpy shaped, some of it is gray and it feels kind of soft. There are white scratches on it, and I can scratch it with my fingernail. It's the biggest and heaviest one.
   CIRCLE GUESS ON SAMPLE: A | B | C | D | E

2. This mineral is colorless and translucent. It has one good cleavage.I can scratch it with my fingernail.
   CIRCLE GUESS ON SAMPLE: A | B | C | D | E

3. This mineral is a translucent purple octahedron (it has 8 triangular faces), but it can be different colors and shapes. It has 4 directions of cleavage. It can be scratched by a steel paperclip, but not by a penny.
   CIRCLE GUESS ON SAMPLE: A | B | C | D | E

4. This mineral is smooth to the touch, with some scratches and a little black line inside.
   CIRCLE GUESS ON SAMPLE: A | B | C | D | E

5. The sample is purple, is longish, has six sides with a broken end, and is really hard.
   CIRCLE GUESS ON SAMPLE: A | B | C | D | E

After you've circled your best guess above, find correct answers in key on class website. Reflect and describe how well you were able to match these descriptions to the right mineral. What's helpful and not helpful in a mineral description? Why? Looking back at your own mineral descriptions and knowing you'll have to identify these same minerals later when we study rocks, what would you change?

***Note: to get credit for this last portion of the lab, all remaining questions have to have the correct answers, so be sure you go back and review past labs if you need to.**

What are the primary differences between a rock and a mineral? (How can you distinguish between them?)

Provide an example of something that can be described as either a rock or a mineral (both) and explain why.

View this Rocks and Minerals Review Lab photo album (find on class website) to answer the remaining questions (use the (i) information link on each photo to see sample #):

Which rocks samples from the above photo album are rocks, and which minerals?
**Do your best. If you're unsure -- just indicate such and why.*

Rocks: *(list sample numbers from photo album)*	**Minerals**: *(list sample numbers from photo album)*

Of the rocks, which rock type is it? What's the evidence?
**Do your best. If you're unsure -- just indicate such and why.*

Igneous Rocks *(list sample numbers from photo album)*
Sedimentary Rocks *(list sample numbers from photo album)*
Metamorphic Rocks *(list sample numbers from photo album)*

Name each rock or mineral:
**Do your best. If you need additional information, just indicate what options the sample could be and what more information you'd need.*

Sample 1:	**Sample 8:**

Sample 2:	**Sample 9:**
Sample 3:	**Sample 10:**
Sample 4:	**Sample 11:**
Sample 5:	**Sample 12:**
Sample 6:	**Sample 13:**
Sample 7:	**Sample 14:**

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	Self-Assessment of Mastery Level	Action plan for improvement
Compare and contrast textures, compositions, and formation environments of igneous, sedimentary, and metamorphic rocks	A | B | C | D | F	
Distinguish between minerals and rocks.	A | B | C | D | F	
Evaluate the effectiveness of a mineral or rock description and generate an effective one.	A | B | C | D | F	
Compare and contrast physical properties of different materials, including density and hardness.	A | B | C | D | F	
Evaluate the challenges in identifying rock and mineral samples collected from your surrounding environment.	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Geologic Time

Geologists piece together Earth history from the geologic record of past events. Events include intrusions and extrusions of igneous rock, crustal metamorphism and deformation accompanying mountain building, and the erosion and deposition of sediments. Information about Earth's geologic history comes largely from exposures of rocks and sediment at the surface called **outcrops**. To understand crustal history, we need to view it in **cross section**, like viewing a slice of it edge on. Outcrops at highway excavations, railroad cuts, stream valleys, and cliffs all provide a cross section of Earth's crust.

Cross sections of sedimentary rocks reveal layers called **strata**. The study of strata is **stratigraphy**. Building the geologic time scale has required modern science to develop techniques to determine the age of rocks, minerals, and sediments. **Relative dating** involves interpreting the sequential relations between different rocks and the events they record. **Radiometric dating** involves calculating the numerical age of certain Earth materials and makes use of the natural phenomenon of radioactivity.

Relative dating is a technique of dating a rock unit relative to other nearby strata. The relative ages of two strata can be fixed in terms of which came first and which second. Those two strata then can be dated relative to a third stratum, and so on. This process continues until all the layers in a cross section are ordered within a relative time scale that reflects a sequence of events.

Each rock in a cross section represents a geologic event in Earth history. Sedimentary rocks, for example, represent events of deposition. A sandstone records an event of sand deposition, either on a shallow continental shelf, beach, or as sand dunes in the desert. Granite records the event of an igneous intrusion in the crust, indicating volcanic activity and magma migration. Schist records an event of high temperature and pressures in the crust, either from deep burial or collision of plates. A geologic event can be any natural occurrence involving geologic materials, including deposition, erosion, deformation (tilting or folding), faulting, intrusion, and others.

The relative ages of many strata in a complex portion of crust can be established through the use of various principles:

The Principle of Original Horizontality describes the general tendency for sediments to be deposited in horizontal beds. If left undisturbed, particles of sediment accumulate in beds that are parallel to this surface. Tilted or folded sedimentary strata record tectonic events that have deformed Earth's crust.

Principle of Original Lateral Continuity describes the tendency for lava flows and sedimentary beds to extend laterally in all directions until they thin to nothing (pinch out) or reach the edge of the deposition basin.

The Principle of Superposition states that the lowest sedimentary rocks in an undisturbed sequence were deposited first and therefore are oldest. Vertical sequences of different rock types are often exposed in cliff faces. If such a sequence is undeformed, the lowest layer of rock is the oldest, and the highest is the youngest. The intervening strata represent a sequence of successive ages between the two extremes.

The Principle of Cross-Cutting Relations describes how certain geologic events (such as folding, faulting, intrusion, and erosion) are younger than the rock bodies they alter. For example, igneous intrusions are younger than the surrounding crustal rock they intrude, and faults are younger than the strata they fracture. It is often possible to determine the relative ages of several mutually cross-cutting intrusions and faults.

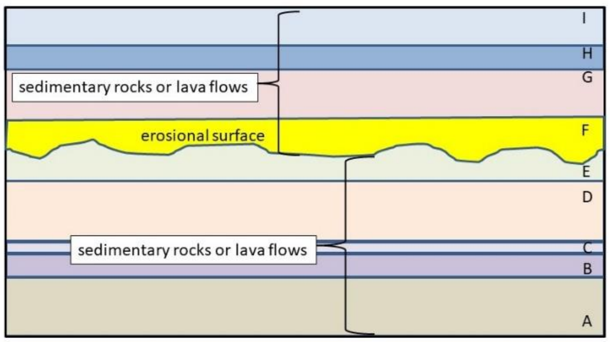
Inclusions are pieces of one rock that you find in another rock. Included rocks must be older than the rocks in which they are found. For example, a cliff face of granite will weather. Pieces of the granite will make their way into beach sand deposits. The sandstone that forms from such deposits must be younger than the granite.
Principles of **unconformities** – Most contacts between adjacent rocks are conformities – meaning that rocks on both sides of the contact formed at about the same time. An unconformity is a rock surface that represents a gap or hiatus in the rock record – like pages missing from a book. Unconformities can occur when there is a pause in sedimentation in an area or when an area has been uplifted and eroded.

Erosion-caused unconformities are often identified by a layer of coarse sediment that remains after the erosional event. This horizon results from the removal of finer, easily eroded material and the formation of a lag deposit, often composed of gravel. Later lithification can turn the layer into a conglomerate bed. In certain strata, the erosional surface stands out because of its unique texture and weathered appearance. In other strata, it might be indiscernible, sometimes leading to erroneous interpretations of the geologic history.

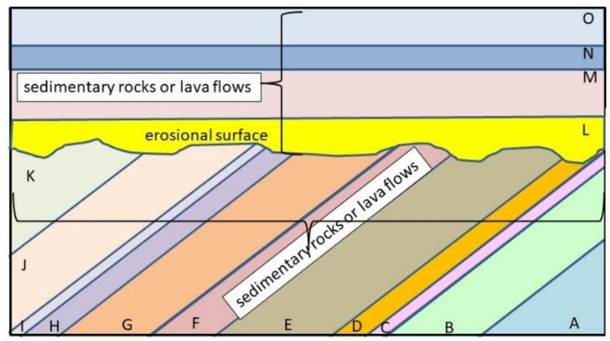
Intervals of nondeposition or erosion can also be identified by a sudden change in rock type. For instance, a sandstone might overlie a shale, with no gradation between the two. Such a drastic change in sedimentary conditions rarely occurs in nature without some intermediate unit, such as a sandy shale or shaly sandstone, recording the change. Thus, a sharp boundary separating two such distinct units can signify an interval of nondeposition, erosion, or both.

Types of unconformities:

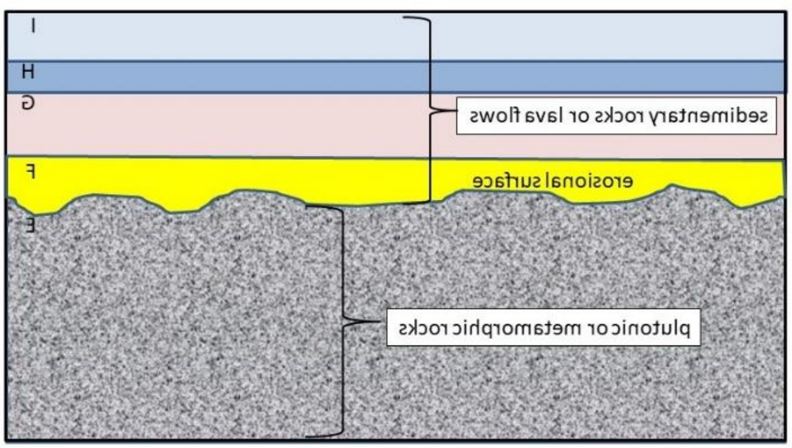
Disconformity – Unconformity between parallel strata or lava flows – usually the contact is irregular and pieces of underlying rock are included in the strata above them.



Angular unconformity – Unconformity between tilted or folded sedimentary layers (or lava flows) below and parallel flat sedimentary layers (or lava flows) above.

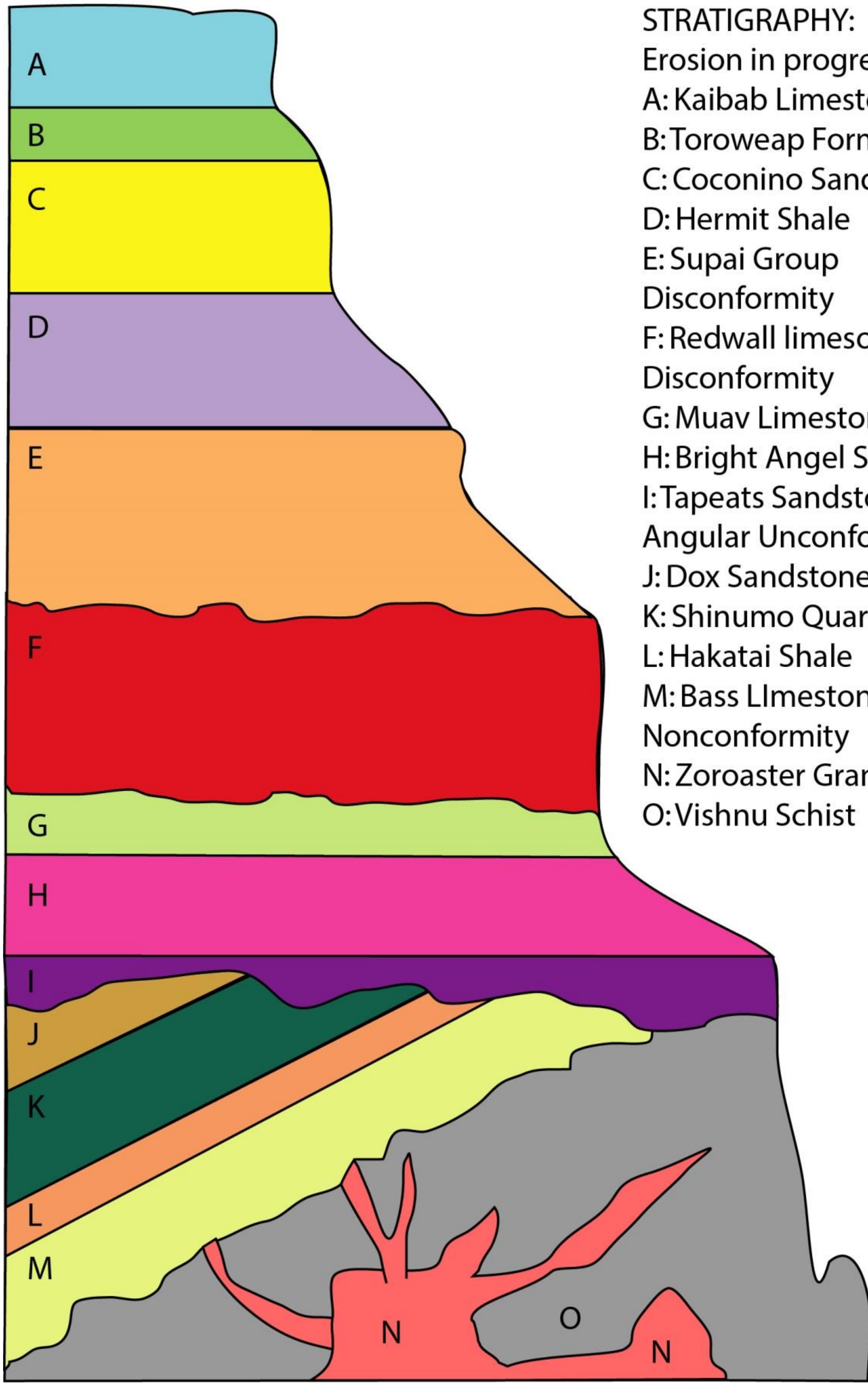


Nonconformity – Unconformity between intrusive igneous rock or metamorphic rock below and flat, parallel sedimentary rock layers (or lava flows) above – due to sediments deposited on top of uplifted and eroded igneous or metamorphic rock.



Stratigraphy

Stratigraphies are a vertical column showing the order of beds and tectonic events. Oldest at bottom; youngest at top; See example below for the Grand Canyon:



STRATIGRAPHY:
Erosion in progress
A: Kaibab Limestone
B: Toroweap Formation
C: Coconino Sandstone
D: Hermit Shale
E: Supai Group
Disconformity
F: Redwall limesone
Disconformity
G: Muav Limestone
H: Bright Angel Shale
I: Tapeats Sandstone
Angular Unconformity
J: Dox Sandstone
K: Shinumo Quartzite
L: Hakatai Shale
M: Bass LImestone
Nonconformity
N: Zoroaster Granite
O: Vishnu Schist

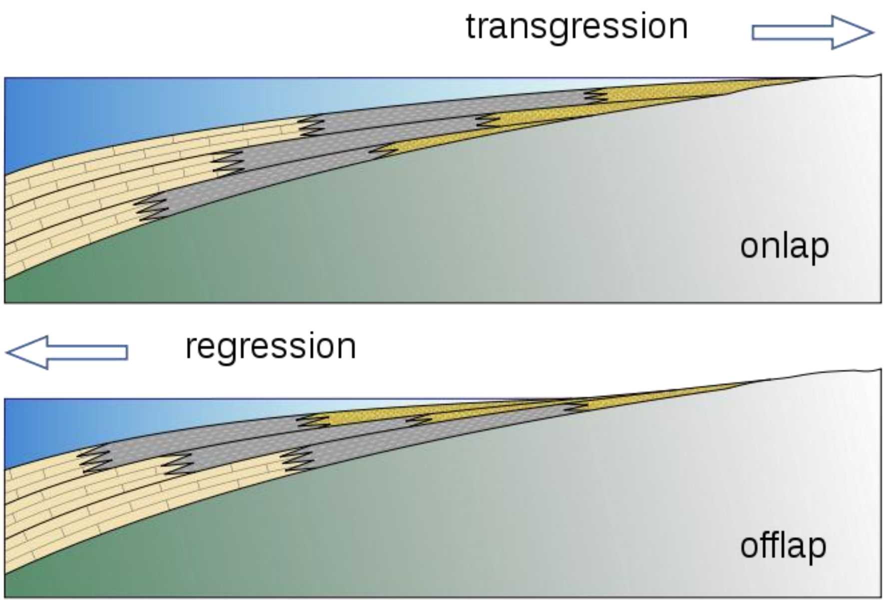
Image: Simplified Geologic Cross-Section Through Grand Canyon (from work done by Peter Coney, USGS.)

Sample FICTITIOUS geologic history of the Grand Canyon Cross-Section.
(This geologic history is provided as an example of how existing rock layers can be linked together by a realistic geological sequence of events. However, there are plenty of other geologic histories that could also explain these layers and only one official one that fits the fossil evidence in the Grand Canyon. The history below is NOT the correct one.)

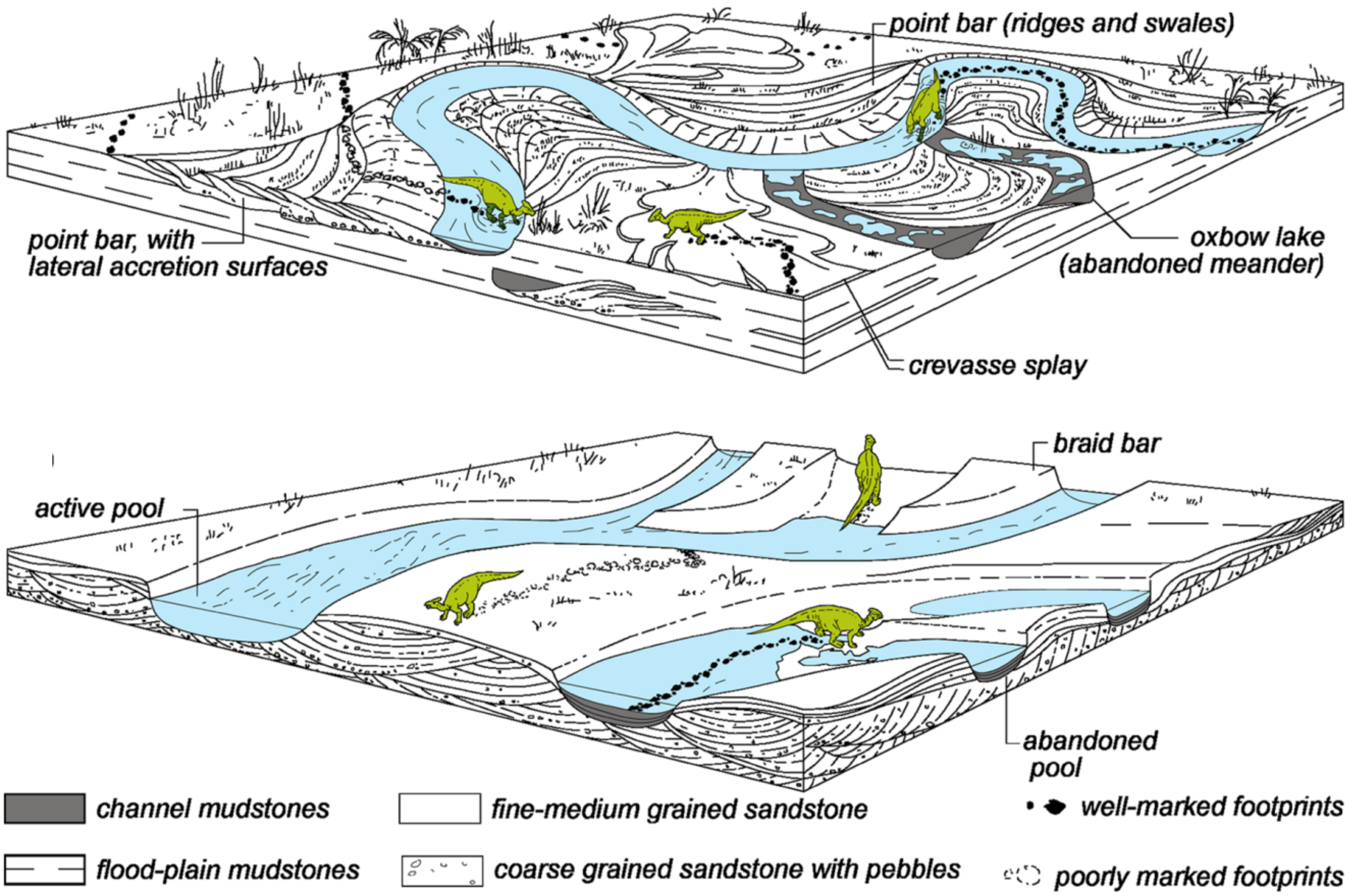
Event	Activity	Geologic Setting	Explanation of how this setting came about
Erosion in progress	Uplift and erosion	River erosion on uplifted river bed.	Additional, previous, unrecorded deposits deposited; Nearby convergent boundary causes tectonic uplift locally. Erosion increases and the unknown deposits removed.
A: Kaibab Limestone	Subsidence and deposition	Coral Reef	Sea level rises – water warm and nutrient poor. No rivers nearby.
B: Toroweap Formation	Subsidence and deposition	Coastal lagoon	Sand spit cuts off region and creates backwater lagoon where sands, muds, and evaporate minerals comingle.
C: Coconino Sandstone	Subsidence and deposition	Wave deposition along ocean beach	Sea level rises – water and waves push sand into area
D: Hermit Shale	Subsidence and deposition	Oxbow lake behind meandering river	River floods and cuts off meander producing lake.
E: Supai Group	Subsidence and deposition	River banks	Sea level drops more, and river bed meanders through area creating flood plains.
Disconformity	Uplift and erosion	Wave erosion of shoreline	Sea level drops and previously deposited and unrecorded sediments are eroded.
F: Redwall Limestone	Subsidence and deposition	Coral Reef	Sea level rises – water warm and nutrient poor. No rivers nearby.
Disconformity	Uplift and erosion	Wave erosion of shoreline	Sea level drops and previously deposited and unrecorded sediments are eroded.
G: Muav Limestone	Subsidence and deposition	Coral Reef	Sea level rises – water warm and nutrient poor. No rivers nearby.
H: Bright Angel Shale	Subsidence and deposition	Lagoon	Spit closes off lagoon. Suspended clays rain down to collect on lagoon floor.
I: Tapeats Sandstone	Subsidence and deposition	Wave deposition along ocean beach	Erosion decreases locally because land now low in elevation. Deposition and subsequent subsidence occurs in low-lying areas.
Angular unconformity	Uplift and erosion	Wave erosion of shoreline	Rift fails. Volcanism stops. Waves erode the fault block mountains.
Beds tilting	Tension	Fault-block mountains	Initiation of continental rifting forms fault-block mountains.
J: Dox Sandstone	Subsidence and deposition	River deposits at delta	Surrounding watershed opens up new area, and new source of sediments come into delta.
K: Shinumo Sandstone	Subsidence and deposition	River deposits at delta	Local river runoff increases as weather brings more precipitation – deposits contain more sand.
L: Hakatai Shale	Subsidence and deposition	River deposits at delta	Local river changes course and delta moves into area.
M: Bass Limestone	Subsidence and deposition	Shell deposits under coral reef (shallow, warm, clear water)	Erosion decreases locally because land now low in elevation. Seawater fills low-lying areas in interior of continent. Coastal environment warms (tropical); water is nutrient poor, so coral reef can grow.
Nonconformity	Uplift and erosion	River erosion on uplifted river bed	Additional, previous, unrecorded deposits deposited; terrane accretion pushes this land inland, away from volcanic arc. Erosion and consequent uplift increase locally and remove the unrecorded deposits.

Event	Activity	Geologic Setting	Explanation of how this setting came about
N: Zoroaster Granite	Volcanism	Deep under subduction zone volcanic arc (continental volcanoes)	Nearby passive margin turns into an active margin, as ocean plate grows old and detaches. Subduction begins. Volcanism inland.
O: Vishnu Schist	Metamorphism	Deep under continent – burial metamorphism	

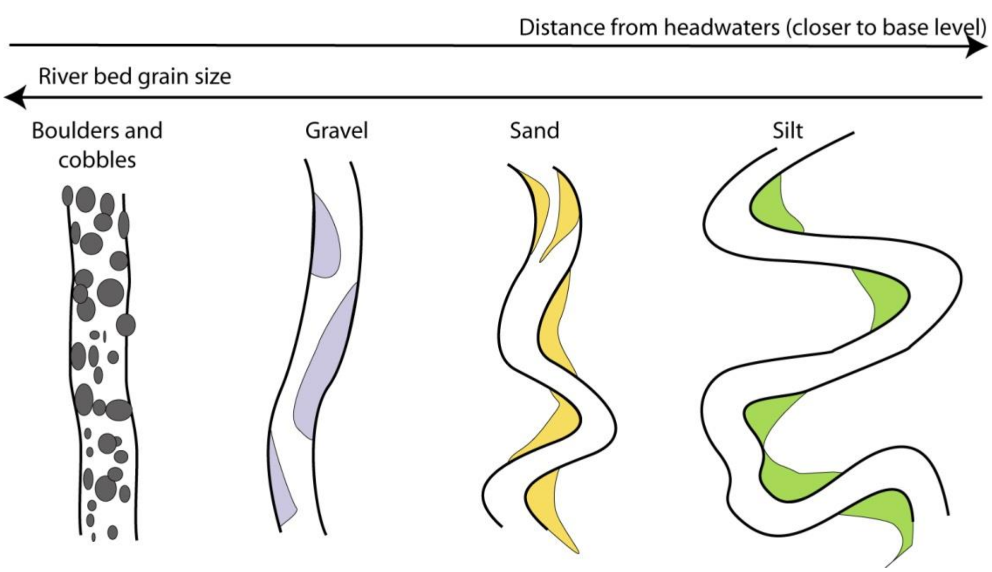
The following pictures should help illustrate the horizontal distribution of different geologic settings and hence methods for settings to change over time



The shift of sedimentary facies during sea-level transgression (creating "onlap" structures) and during sea-level regression (creating "offlap" structures). Brick pattern offshore represents mud-sized calcareous shells. Grey pattern in middle represents muds. Yellow pattern near shore represents sands. Image: Woudloper –Copyright: CC BY-SA 1.0



River sediments – variations as a river changes course. Note the buried sediments representing different parts of the river channel/floodplains as the river changed course throughout its history.
Image from: The Latest Succession of Dinosaur Track sites in Europe: Hadrosaur Ichnology, Track Production and Palaeoenvironments. 2013 Vila et al..



River bed grain sizes – changes as the rivers evolve from steep and straight (headwaters) to flat and meandering (mouth).

Radiometric dating
We can use radioactive dating only on specific rocks – ones that contain radioactive isotopes (like those listed in the table below) – and ones that can maintain a closed system – no atoms lost or gained. Not all rocks can be dated. Not all rocks contain useful isotopes for dating.

When radioactive parent isotopes (P) decay, they produce daughter products (D) at a constant rate, called the half-life (**T)**. Example: if we start with 84 atoms of a particular parent, after one half-life (say 10 years), there will be 42 parent atoms remaining and 42 daughter atoms newly made. After another half-life (another 10 years, for a total of 20 years), there will be 21 parent atoms remaining and now 63 daughter atoms. Each parent-daughter isotope pair has its own half-life. To achieve the above example with U-238 takes 9 billion years. To achieve the above example with C-14 takes 11400 years.

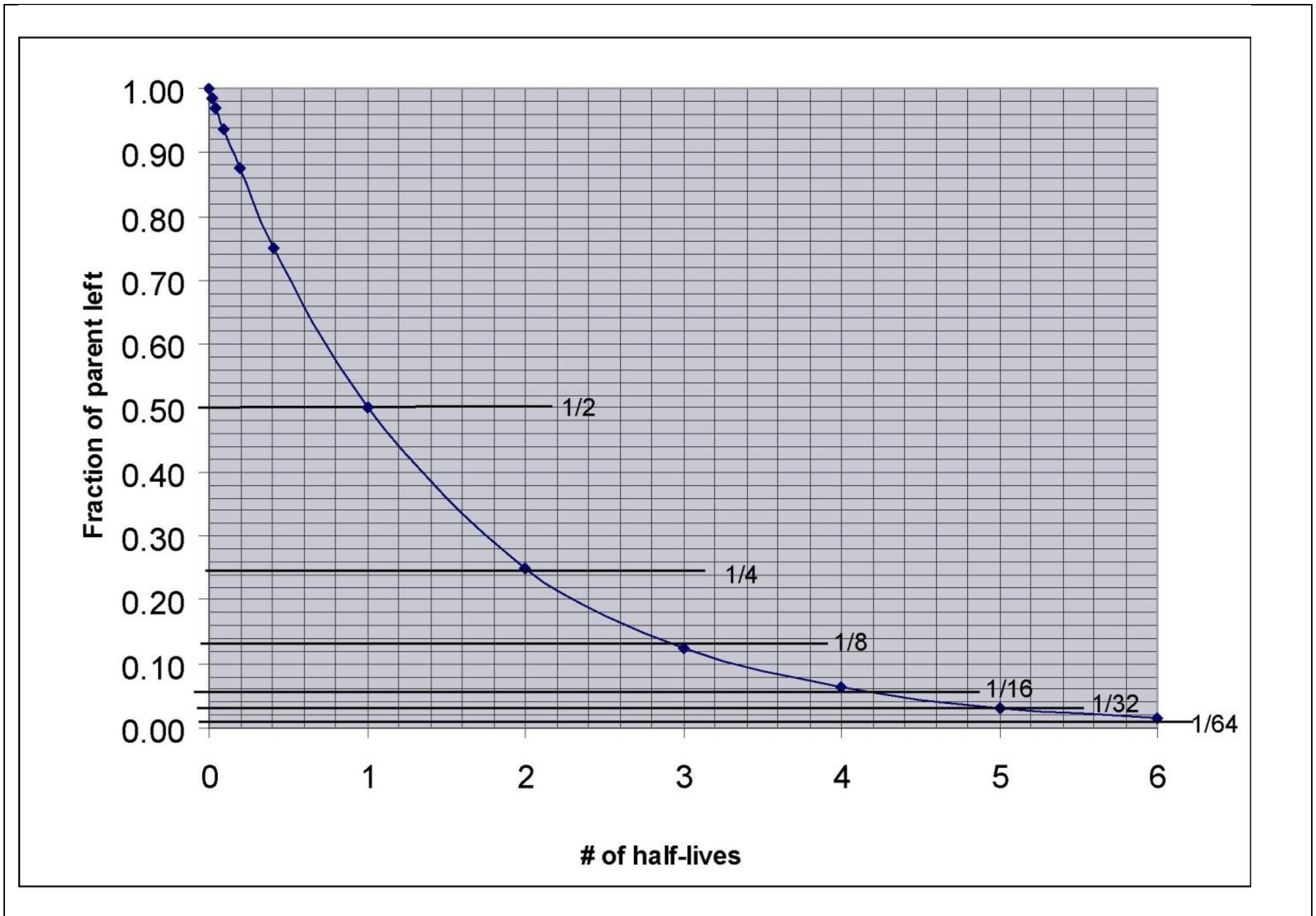
In the geologic environment, we use a mass spectrometer to count the number of Parent and Daughter atoms in a closed-system substance (like minerals crystallizing from magmas), and use the relative proportions to calculate the age of the closed-system. For example: If the ratio of P:D is 1:1, that means there are equal amounts of each: 50% P and 50% D (or ½ P and ½ D). One half life has passed. If the ratio is 1:3, there is 75% D, 25% P (or ¼ P, ¾ D): two half-lives have passed.

Useful isotopes for dating

Parent (P)	Daughter (D)	Half-lives ($T_{1/2}$)	Materials dated
U-238	Pb-206	4.5×10^9 yr	Zircon (felsic igneous rocks – source; and sedimentary rocks as grains)
U-235	Pb-207	0.7×10^9 yr	
K-40	Ar-40	1.4×10^9 yr	Micas, volcanic rock (igneous rocks)
C-14	N-14	5700 yr	Shells, limestone, organic materials

Calculating radioactive age
If you want to date the age of a shell in an archeological dig, which isotope pair would you measure? You'd use C14-N14 because the age range fits. Ancient man isn't more than 100,000 years old. Using any other isotope pair would be prone to error.

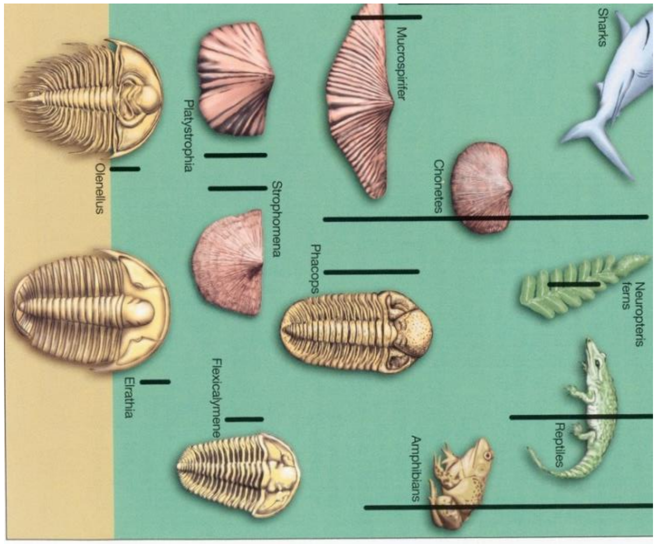
If such a measurement was made, and the P:D ratio was found to be 1:7, how old is the sample? Out of 8 parts, 1 is P and 7 are daughter. That means that 1/8 or 12.5% of the parent is remaining. Such occurs after 3 half lives. C14-N14 half-life is 5700 years, so the shell is 5700 x 3 = 17100 years old.



T	1	2	3	4	5	6
P:D	½:½	¼:¾	1/8:7/8	1/16:15/16	1/32:31/32	1/64:63:64
P:D	1:1	1:3	1:7	1:15	1:31	1:63

T (# of)	**Fraction**			
Half lives	**Parent**	**Daughter**	**Ratio**	
0	1	0	infinity	:1
0.0227	63/64	1/64	63	:1
0.0458	31/32	1/32	31	:1
0.0931	15/16	1/16	15	:1
0.1927	7/8	1/8	7	:1
0.4151	3/4	1/4	3	:1
1.0000	1/2	1/2	1:	1
2.0000	1/4	3/4	1:	3
3.0000	1/8	7/8	1:	7
4.0000	1/16	15/16	1:	15
5.0000	1/32	31/32	1:	31
6.0000	1/64	63/64	1:	63

CURVE EQUATION: $T = -1.443\ln(f)$
f = fraction of parent left;
T = # of half lives that have passed



(image modified from Laboratory Manual in Physical Geology, Busch Ed., Prentice Hall Pub., 1997)

The principle of faunal succession

Fossils found in sedimentary rock layers can be used to relatively date these layers, when compared with the evolutionary record. Flora and fauna fossils succeed each other in a reliable order. For example, a fossilized ammonite will never be found in the same rocks as dinosaurs, as ammonites lived and went extinct many millions of years before dinosaurs lived. Note: not all fossils are good indicators of age. For example, stromatolites have existed on planet Earth since 3.5 billion years ago (still exist today), so they cannot uniquely place or order rocks younger than 3.5 billion years old. However, other fossils, known as index fossils, are of flora or fauna that lived for very short periods of time. These index fossils are most useful for relatively dating rocks.

Image below: Fossil assemblages (not to scale)

	Precam	**Paleozoic**							**Mesozoic**			**Cenozoic**	
		Cambr	**Ordovi**	**Siluria**	**Devoni**	**Mississ**	**Pennsy**	**Permi**	**Triassic**	**Jurassi**	**Cretac**	**Tertiar**	**Quater**
(period starts)	**4.6 Ga**	**570 Ma**	**505 Ma**	**438 Ma**	**408 Ma**	**360 Ma**	**320 Ma**	**286 Ma**	**245 Ma**	**208 Ma**	**144 Ma**	**66.4 Ma**	**1.6 Ma**
Humans													xx
Fagopsis trees												xxx	
Mammals									xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx				
Dinosaurs									xxxxxxxxxxxxxxxxxxxxxxxxxxx				
Neurop.ferns							xxxxxx						
Reptiles							xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx						
Sharks					xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx								
Amphibians					xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx								
Mucrospirifer (b)					xxxxxxxxxx								
Chonetes (b)				xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx									
Phacops (t)				xxxxxxxxxxxxxxx									
Flexicalymene (t)			xxxxxx										
Platystrophia (b)			xxxxxxxxx										
Elrathia (t)		xxxx											
Olenellus (t)		xxxx											

(b) = brachiopod species; (t) = trilobite species

Geologic Time Prereading Homework

Scientific notation

Scientific notation is a simpler way of writing numbers with many digits (really big or really small). Scientific notation moves the decimal point to a new point where there is only one single digit to the left of the decimal and then multiplies that number by a power of 10, where the power is the number of places the decimal moved. *(a positive power if movement was to the left, meaning the overall value of the number is larger than 1; a negative power if movement was to the right, meaning the overall value of the number is less than 1).*

For example, 0.00023 cm becomes 2.3×10^{-4} cm | 10023 cm becomes 1.0023×10^{4} cm 4500 cm = 4.5×10^{3} cm | 0.06780 cm = 6.780×10^{-2} cm

1. Write in scientific notation: 0.0000237 cm	2. Write in scientific notation: 120,400 cm
3. Write out (expanded): 2.5×10^{-6} cm	4. Write out (expanded): 3.9×10^{4} cm

In the earth sciences, after converting large numbers to scientific notation, we will try to replace the powers of 10 portion with the words thousands, millions, or billions to make it easier to read. E***xamples***:

1,000 = 1×10^{3} = 1 thousand	1,000,000 = 1×10^{6} = 1 million	1,000,000,000 = 1×10^{9} = 1 billion

To change 3.4×10^{11} to billions, 10^{9}, subtract 2 from the exponent and balance by adding two places to the decimal. Answer: 340 $\times 10^{9}$ = 340 billion. To change 3.4×10^{5}, to millions, 10^{6}, add 1 to the exponent and balance by losing one decimal place. Answer: 0.34×10^{6} or 0.34 million.

5. Change 5.68×10^{8} years to a number with the unit: billion years.	6. Change 3.2×10^{10} years to a number with the unit: billion years.
7. Change 5.68×10^{8} years to a number with the unit: million years.	8. Change 3.2×10^{5} years to a number with the unit: million years.

Adding, Subtracting, Dividing, and Multiplying with scientific notation: ***(Solve these without a calculator!)***

When multiplying, add exponents: $(2 \times 10^{2}) \times (3 \times 10^{3}) = 2 \times 3 \times 10^{2} \times 10^{3} = 6 \times 10^{5}$. When dividing, subtract exponents: $(2 \times 10^{2}) \div (3 \times 10^{3}) = (2 \div 3) \times (10^{2} \div 10^{3}) = 0.67 \times 10^{-1} = 0.067$. When adding or subtracting, exponents must be the same first: $(2 \times 10^{2}) + (3 \times 10^{3}) = (2 \times 10^{2}) + (30 \times 10^{2}) = 32 \times 10^{2} = 3.2 \times 10^{3}$

9. $(5 \times 10^{3}) \times (6 \times 10^{5})$ =	10. $(8 \times 10^{9}) \div (2 \times 10^{6})$ =
11. $(5 \times 10^{3}) + (6 \times 10^{4})$ =	12. $(8 \times 10^{9}) - (2 \times 10^{7})$ =

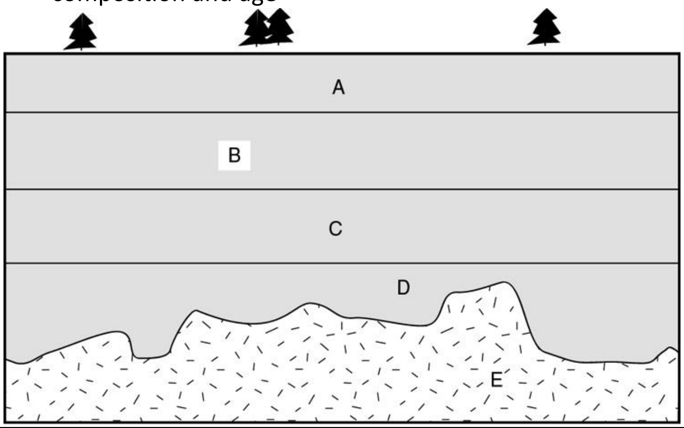
Radiometric Dating

13. If the ratio of P:D in a mineral is 1:7, how many half-lives have passed?	14. If the ratio of P:D in a mineral is 15:1, how many half-lives have passed?
15. If the half-life for the above PD pair is 7 million years (precise to 100,000 years), how old is the mineral? Show work.	16. If the half-life for the above PD pair is 500 million years (precise to 10 my), how old is the mineral? Show work.

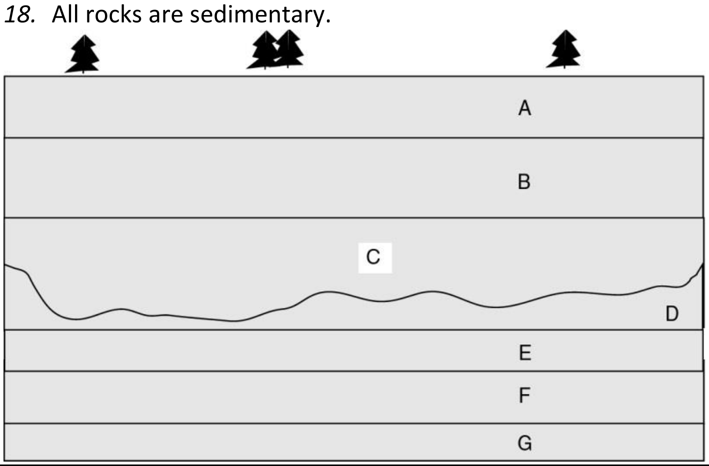
Relative Dating

Order rocks from oldest to youngest. List stratigraphy in margin (youngest on top; oldest on bottom). Label, name, and include all unconformities and tilting or folding events in stratigraphy.

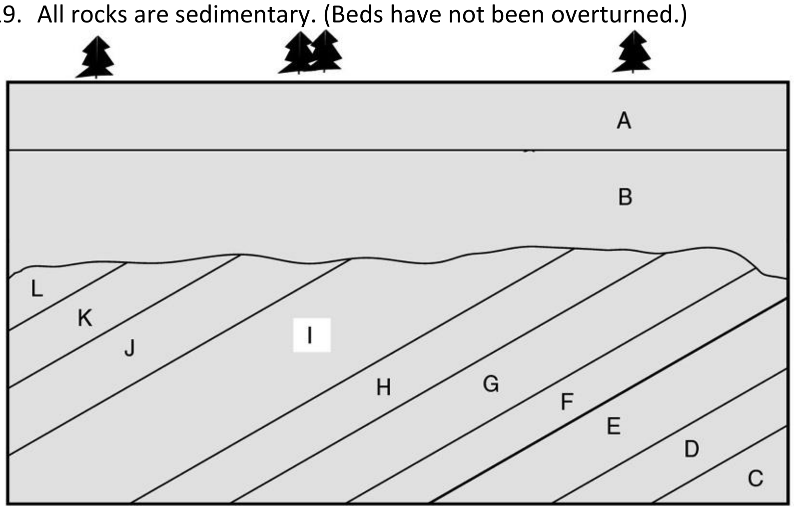
17. The rocks in contact with E (a granite) show NO evidence of contact metamorphism, but do contain inclusions of E's composition and age



18. All rocks are sedimentary.



19. All rocks are sedimentary. (Beds have not been overturned.)



20. **Which is older? (Circle)** shale with fagopsis trees and reptiles OR shale with neuropteris ferns and amphibians OR Can't be determined	21. **Which is older? (Circle)** shale with dinosaurs and reptiles OR a shale with mammals and reptiles OR Can't be determined

Geologic Time Lab Exercises

Using Fossils to relatively date rocks (Using Index fossil sheet from prereading, answer these questions)

1.	What is the possible age range of a shale that contains fossils of dinosaur, shark, and mammals?
2.	What is the possible age range of a shale that contains fossils of amphibians?
3.	Give approximate ages to these rock layers and then order them based on age with (1) = youngest and (8) = oldest. (Some you might not be able to definitively order because of overlapping age ranges – *do not guess or obscure such information* – indicate the problems.)

Rock type	**Fossils present**	**Age range (m.y.)**	**Order**
Limestone	Platystropia, flexicalymene		
Mudstone A	Elrathia		
Mudstone B	Sharks, dinosaurs, mammals		
Mudstone C	Sharks, chonetes, neuropteris ferns, reptiles		
Sandstone A	Sharks, dinosaurs		
Sandstone B	Olenellus		
Shale A	Sharks, chonetes, phacops, mucrospirifer, amphibians		
Shale B	Fagopsis trees, sharks		

Radioactive Dating (Answers must be in billions or millions or thousands of years. Show all work.)

4.	Study of a rhyolite's zircon crystals shows that of all U-235 and Pb-207 atoms, 25% are U-235 and 75% are Pb-207. How old is the zircon? (Assume Half-Life precise to 10 my.)
5.	An old rhyolite lava flow contains zircon minerals and is present in a sequence of rock layers exposed in a cliff. A mass spectrometer analysis counted atoms of U-235 and Pb-207 in the Zircon and revealed 12.5% of atoms were U-235 and 87.5% Pb-207. 87.5% of the U-235 atoms decayed to Pb-207. What is the age of the zircon crystals? (Assume Half-Life precise to 10 my.)
6.	What is the age of the rhyolite? (Is it the same as the age of the zircon crystals? Why or why not?)
•	What do we know about the age of rocks above the rhyolite?
•	What do we know about the age of rocks below the rhyolite?
7.	An igneous rock contains muscovite and is present in a sequence of rock layers exposed in a cliff. A mass spectrometer analysis counted atoms of K-40 and Ar-40 in the mineral and revealed a ratio of 1:7. What is the age of the rock? (Assume Half-Life precise to 100 my.)

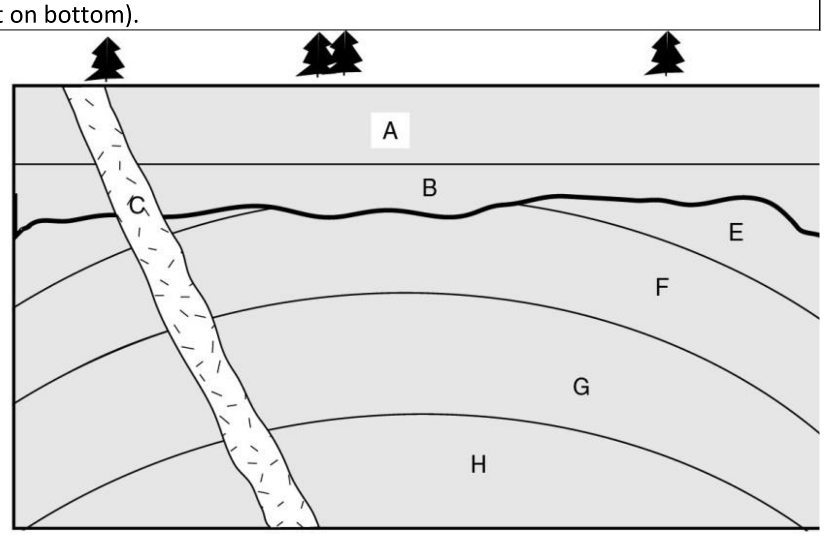
8. A sedimentary rock contains zircon minerals and is present in a sequence of rock layers exposed in a cliff. A mass spectrometer analysis counted atoms of U-235 and Pb-207 in the Zircon and revealed 90% of atoms were U-235 and 10% Pb-207. 10% of the U-235 atoms decayed to Pb-207. What is the age of the zircon crystals? (Assume Half-Life precise to 10 my.)	
9. What is the age of the rock? (Think about what the age of sedimentary minerals means about the age of the sedimentary rock. Where did the zircon come from originally?)	
10. Why don't we try to date minerals in metamorphic rocks?	
11. We think that the Earth probably formed about the same time as all the other rocky materials in the solar system, including the oldest meteorites. If we can radioactively date a meteorite, we can approximate the age of the Earth. The oldest meteorites ever found contain nearly equal amounts of both U-238 and Pb-206. What is the presumed age of Earth? Why?	
12. Carbon in a buried peat bed has only 6.25% of the C-14 that we find in modern shells. If we assume that global inventory of radiocarbon (carbon formed by cosmic rays in the atmosphere and then dissolved in sea water) has remained constant, what is the age of the peat bed? Explain. (Assume Half-Life precise to 100 years.)	

Relative Dating

13. Order rocks from oldest to youngest. Label, name, and include in your stratigraphy all unconformities. List stratigraphy on left (youngest on top; oldest on bottom).

All rocks are sedimentary, except C, which is a dike. Rocks in contact with C show evidence of contact metamorphism.

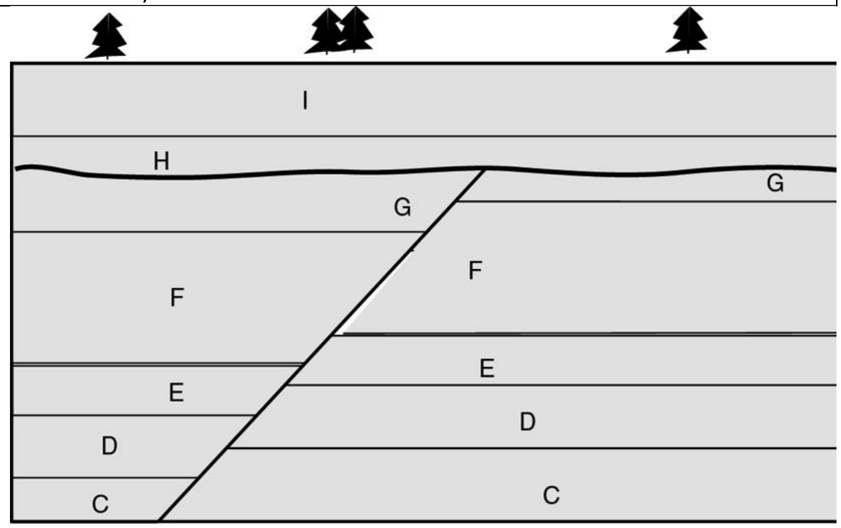
STRATIGRAPHY



14. Order rocks from oldest to youngest. Label, name, and include in your stratigraphy all unconformities and faults. List stratigraphy on left (youngest on top; oldest on bottom).

All rocks are sedimentary.

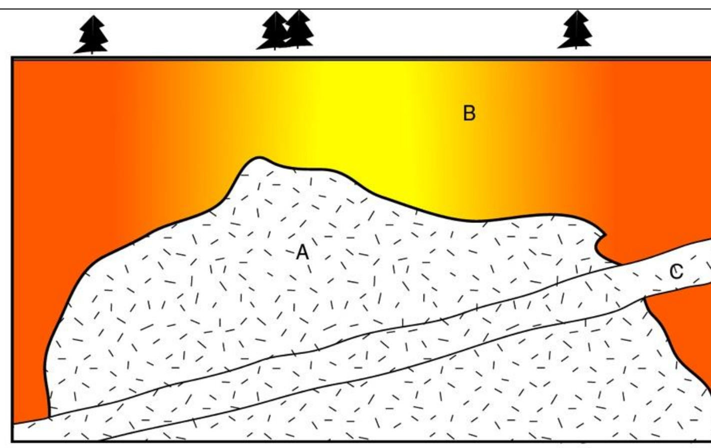
STRATIGRAPHY



15. (Same instructions as question above.)

A is a batholith. C is a dike. B is a schist.

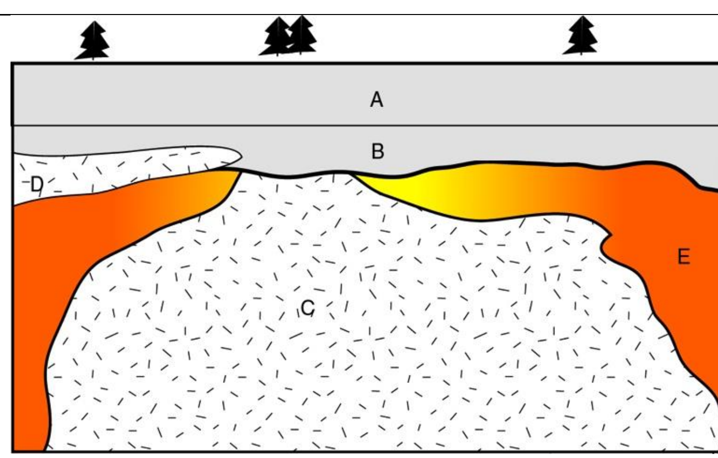
STRATIGRAPHY



16. (Same instructions as question above.)

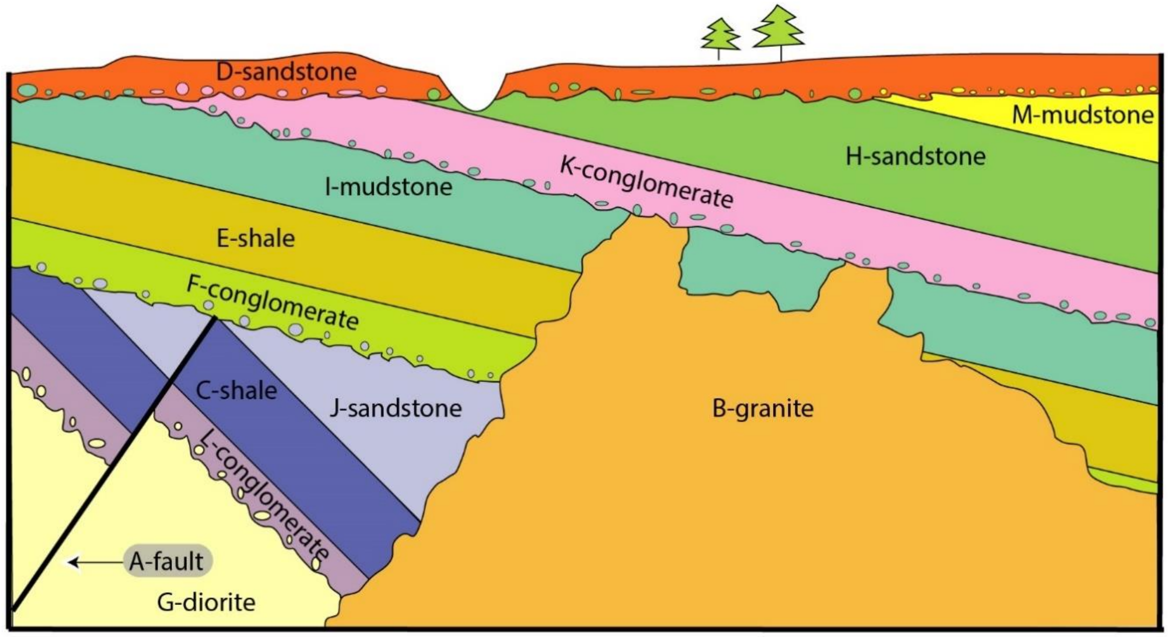
C is a batholith. D is a sill-like intrusion. A and B are sedimentary. E is schist.

STRATIGRAPHY

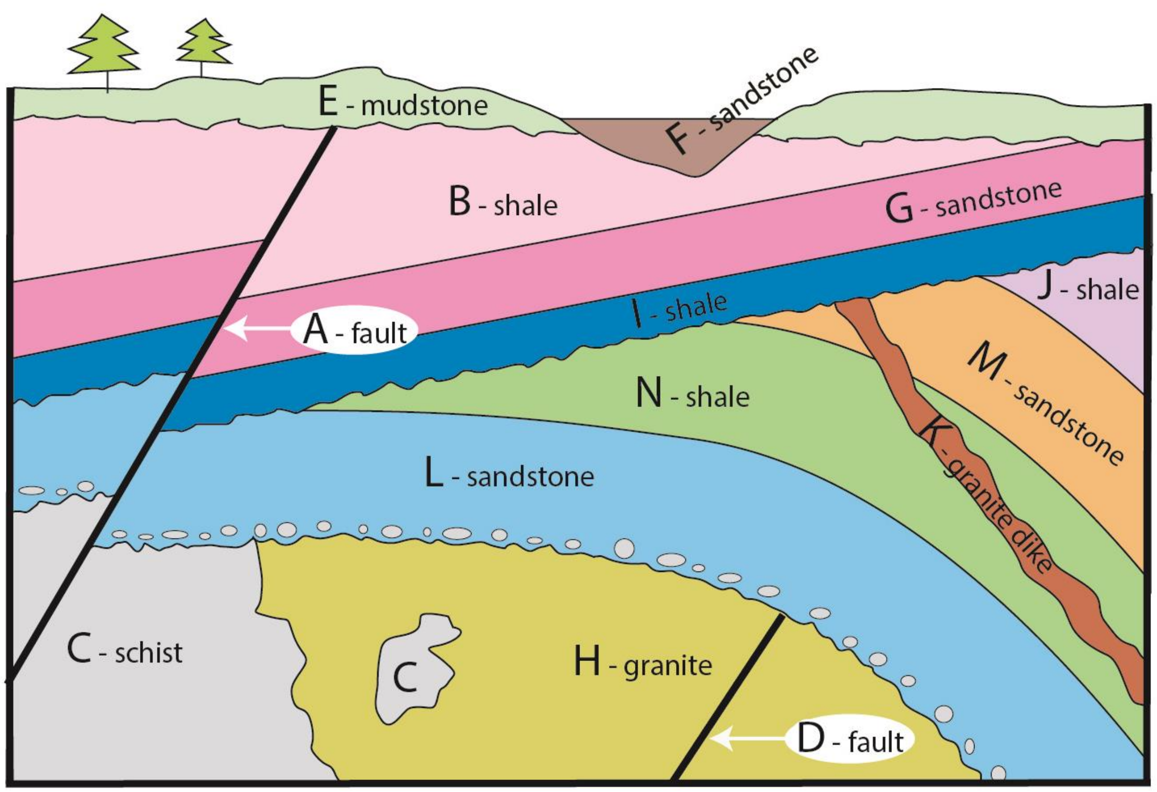


17. Order all rocks, faults, **folds**, intrusions, etc. in each of these figures. Label, name, and include in your stratigraphy all unconformities. List stratigraphy on left (youngest on top; oldest on bottom).

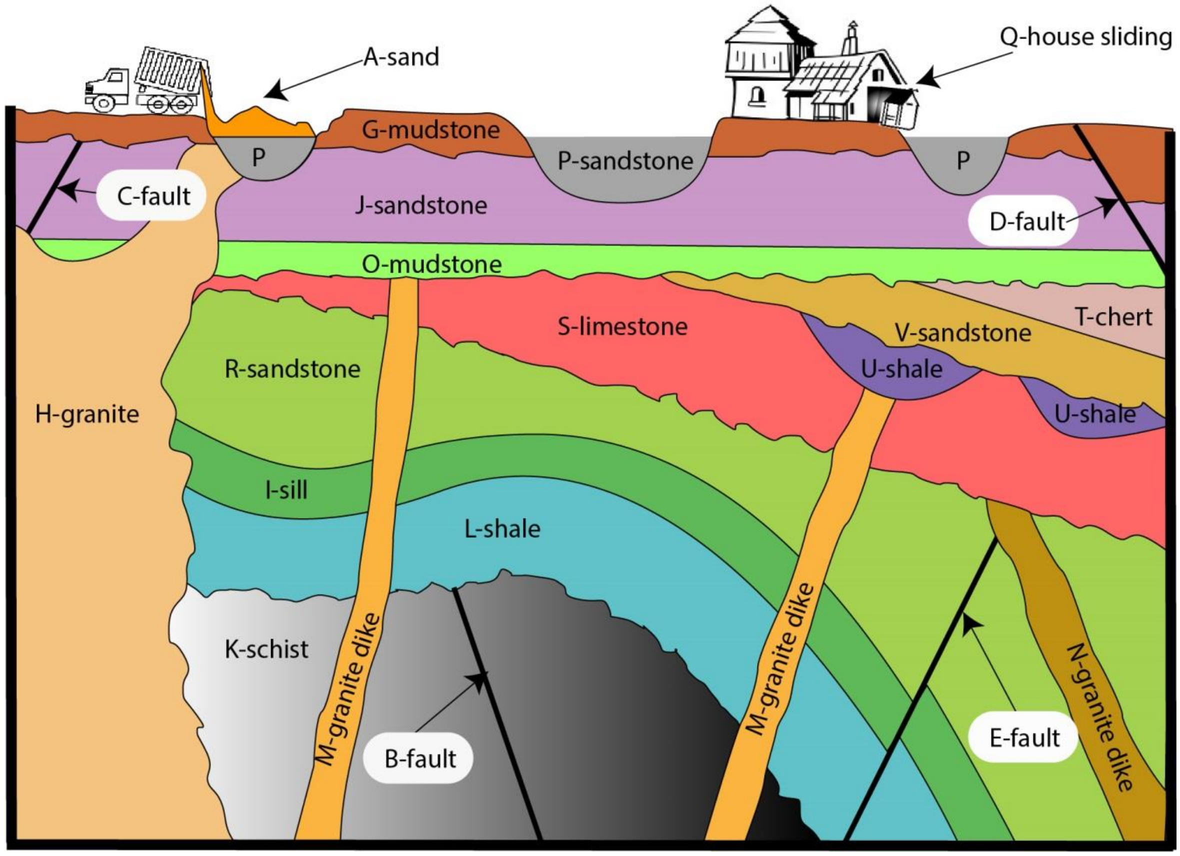
STRATIGRAPHY



STRATIGRAPHY



STRATIGRAPHY



Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Order the relative ages of all rock formation, fault, fold, and erosional (unconformity) events in a geologic cross-section	A | B | C | D | F	
Apply faunal succession to estimate the relative ages of rocks found with varying combinations of fossil organisms	A | B | C | D | F	
Calculate the radiometric age of rocks of a given parent:daughter isotope ratio for a variety of isotope pairs	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

Geologic Time Practice Sheet

Using Fossils to relatively date rocks (Using index fossil sheet, answer these questions)

1. What is the possible **age range** of a shale that contains fossils of mucrospirifer and phacops?	
2. What is the possible **age range** of a shale that contains fossils of sharks?	
3. Which is older: shale that contains fossils of fagopsis trees and mammals? OR shale with human fossils??	
4. Which is older: shale with chonetes and phacops OR shale with chonetes and mucrospirifer?	

5. Write in scientific notation: 56,078	6. Write in scientific notation: 0.0136
7. Write out (expanded): 1.11×10^4	8. Write out (expanded): 3.9×10^{-2}
9. 1.11×10^{11} years = ____________ billion yr	10. 1.11×10^5 years = ______________ million years
11. 2.3×10^7 years = ______________ million yr	12. 2.3×10^8 years = ______________ billion years
13. $(3 \times 10^6) \times (5 \times 10^5) =$	14. $(9 \times 10^8) \div (6 \times 10^2) =$
15. $(4 \times 10^4) + (3 \times 10^3) =$	16. $(2 \times 10^9) - (9 \times 10^8) =$

Radioactive Dating (Answers must be in billions or millions or thousands of years. Show all work.)

17. If the ratio of P:D in a mineral is 3:1, how many half-lives have passed?	
18. If the half-life for the above PD pair is 20 million years (precise to 1 my), how old is the mineral? Show work.	
19. If the ratio of P:D in a mineral is 1:15, how many half-lives have passed?	
20. If the half-life for the above PD pair is 200 million years (precise to 10 my), how old is the mineral? Show work.	
21. Study of a rhyolite's zircon crystals shows that of all U-235 and Pb-207 atoms, 88% are U-235 and 12% are Pb-207. (Half-life is 700 million years – precise to 10 my.) How old is the zircon?	
22. A volcanic rock contains zircon minerals and is present in a sequence of rock layers exposed in a cliff. A mass spectrometer analysis counted atoms of U-235 and Pb-207 in the Zircon and revealed 33% of atoms were U-235 and 67% Pb-207. 67% of the U-235 atoms decayed to Pb-207. What is the age of the zircon crystals?	
23. What is the age of the rock? (Is it the same as the age of the zircon crystals? Why or why not?)	

• What do we know about the age of rocks above the flow?	
• What do we know about the age of rocks below the flow?	
24. An igneous rock contains muscovite and is present in a sequence of rock layers exposed in a cliff. A mass spectrometer analysis counted atoms of K-40 and Ar-40 in the mineral and revealed a ratio of 1:3. (Half-life is 1.4 x 10^9 yr – precise to 100 my.) What is the age of the rock?	
25. A sedimentary rock contains a coal seam with fossils and is present in a sequence of rock layers exposed in a cliff. A mass spectrometer analysis counted atoms of C-14 and N-14 in the coal seam fossils and revealed a C-14:N-14 ratio of 1:25. (Half-life is 5700 yr. precise to 100 yr) What is the age of the coal seam?	
26. A zircon in a sedimentary rock has been analyzed with a mass spectrometer and found to have a U235:Pb207 ratio of 2:1? The zircon displays no chemical weathering or metamorphism. How old is the zircon?	
27. What is the age of the rock that contains the zircon?	

Relative Dating

For all the images below, order rocks from oldest to youngest. List stratigraphy in margin (youngest on top; oldest on bottom). Label, name, and include all unconformities and tilting or folding events in stratigraphy.

28. Rocks E and C are sedimentary. Faults A and F need names and orders. D is a dike. B is a granite batholith.

STRATIGRAPHY

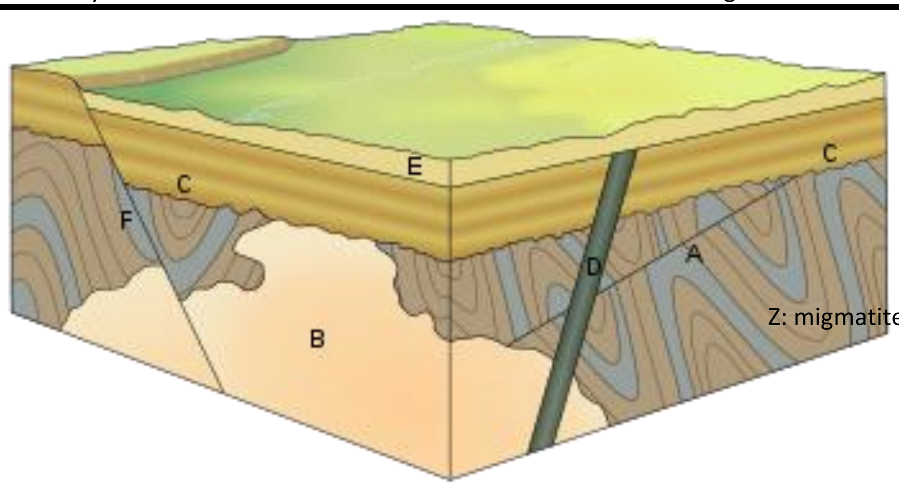


Image: Woudloper –Copyright: CC BY-SA 1.0

29.

STRATIGRAPHY

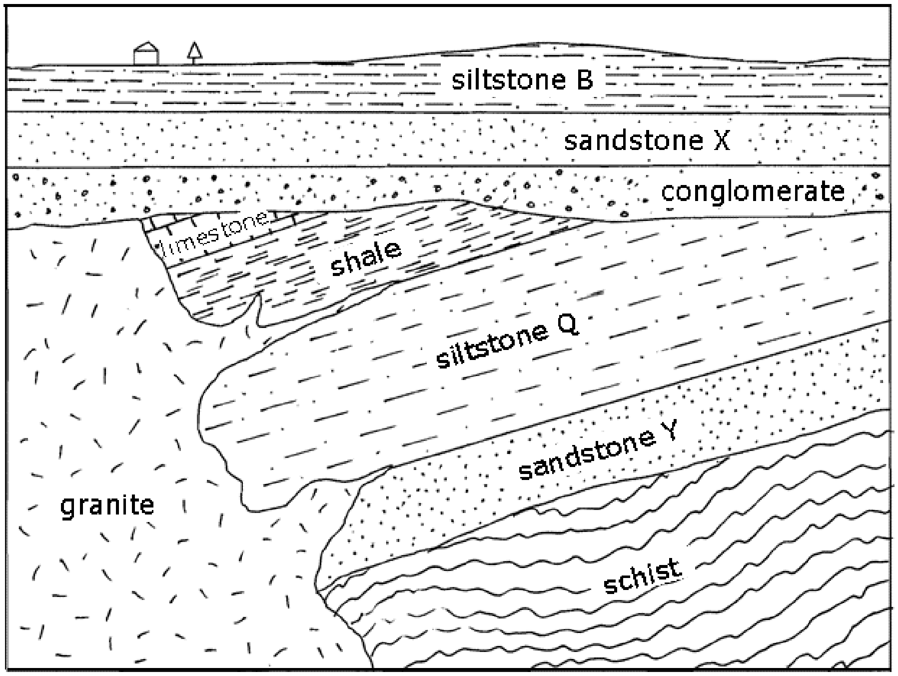


Image: Ralph Dawes and Cheryl Dawes Copyright: CC BY-SA 3.0

30. **Brick pattern** is limestone. **Point pattern** is for sandstones.
Dashed horizontal lines are for shale. Dashed lines in all directions are for a basalt dike.

STRATIGRAPHY

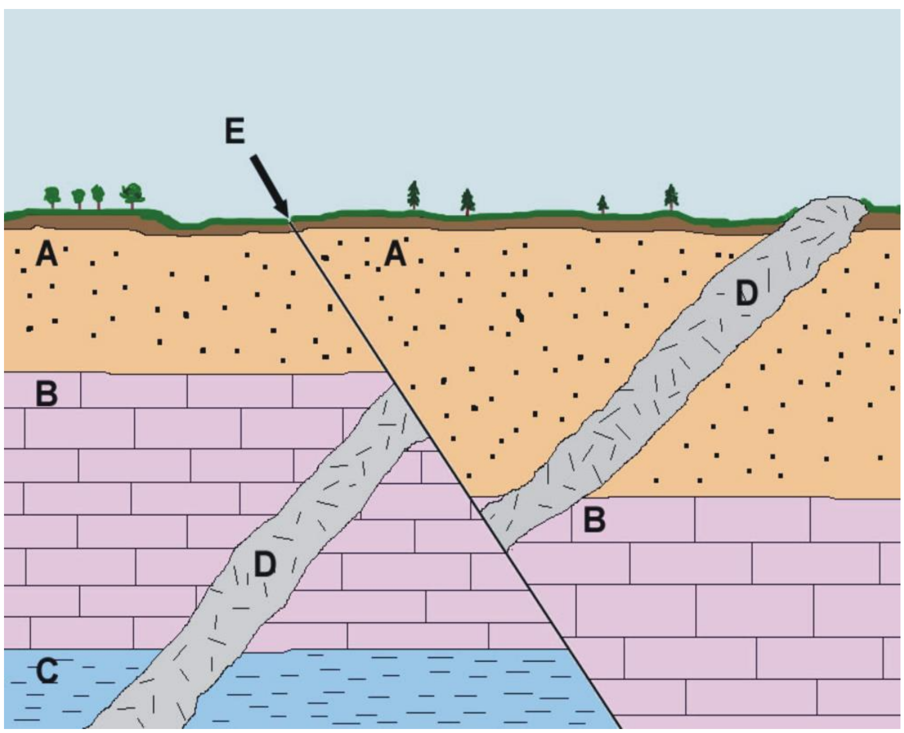


Image: Kurt Rosenkrantz Copyright: CC BY-SA 3.0

31. Do your best to recognize, name, and order different rock types in this cross-section.

STRATIGRAPHY

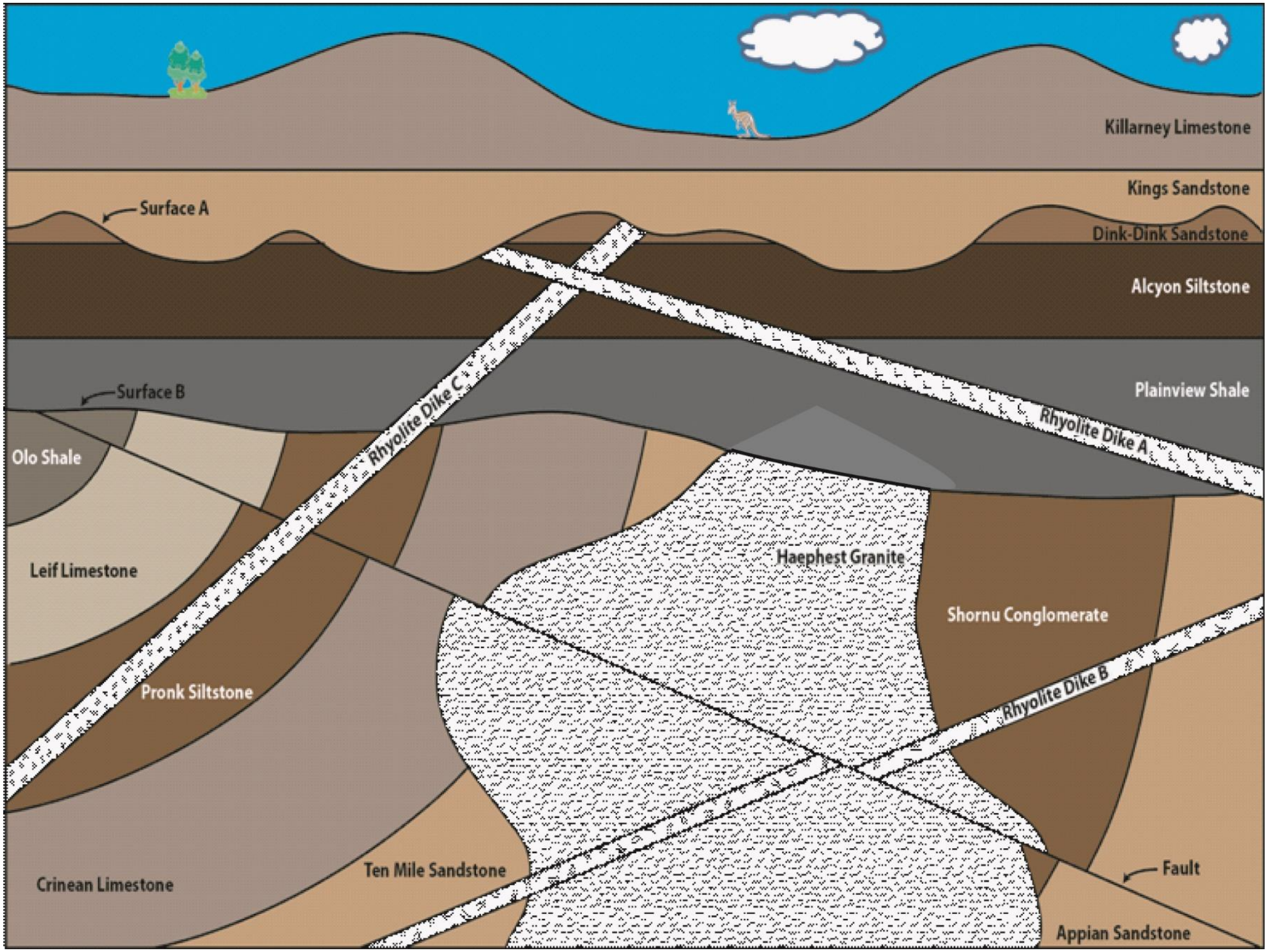


Image: Modified from one provided by Scott K. Johnson – Creative Commons – CC BY-SA 3.0

KEY

Using Fossils to relatively date rocks (Using index fossil sheet, answer these questions)

1. What is the possible **age range** of a shale that contains fossils of mucrospirifer and phacops?	408 to ~350 Ma
2. What is the possible **age range** of a shale that contains fossils of sharks?	<=360 Ma
3. Which is older: shale that contains fossils of fagopsis trees and mammals? OR shale with human fossils?	Shale with fagopsis trees and mammals
4. Which is older: shale with chonetes and phacops OR shale with chonetes and mucrospirifer?	Can't be sure

5. Write in scientific notation: 56,078 ***5.6078×10^4***	6. Write in scientific notation: 0.0136 ***1.36×10^{-2}***
7. Write out (expanded): 1.11×10^4 ***11100***	8. Write out (expanded): 3.9×10^{-2} ***0.039***
9. 1.11×10^{11} years = ***111*** billion years	10. 1.11×10^5 years = ***0.111*** million years
11. 2.3×10^7 years = ***23*** million yr	12. 2.3×10^8 years = ***0.23*** billion years
13. $(3 \times 10^6) \times (5 \times 10^5)$ = ***$15 \times 10^{11} = 1.5 \times 10^{12}$***	14. $(9 \times 10^8) \div (6 \times 10^2)$ = ***1.5×10^6***
15. $(4 \times 10^4) + (3 \times 10^3) =$ $4 \times 10^4 + 0.3 \times 10^4 = 4.3 \times 10^4$	16. $(2 \times 10^9) - (9 \times 10^8) =$ $2 \times 10^9 - 0.9 \times 10^9 = 1.1 \times 10^9$

Radioactive Dating (Answers must be in billions or millions or thousands of years. Show all work.)

17. If the ratio of P:D in a mineral is 3:1, how many half-lives have passed?	T=-1.443ln(f) f – fraction of parent left F=3/4 T=-1.443ln(.75)= 0.41513 = 0.415 Range: -1.4434ln.75 =0.41524 | 1.4425ln.75 =0.41498 (or, from graph, .75 parent ~ 0.4 half lives
18. If the half-life for the above PD pair is 20 million years (precise to 1 my), how old is the mineral? Show work.	0.4 half-lives x 20 million years = 8 m.y. OR 0.415 x 20 my = 8.30 my = 8.3 my = 8 my
19. If the ratio of P:D in a mineral is 1:15, how many half-lives have passed?	4
20. If the half-life for the above PD pair is 200 million years (precise to 10 my), how old is the mineral? Show work. .	4 half-lives x 200 million years = 800 m.y.
21. Study of a rhyolite's zircon crystals shows that of all U-235 and Pb-207 atoms, 88% are U-235 and 12% are Pb-207. (Half-life is 700 million years – precise to 10 my.) How old is the zircon?	From graph, 88% parent ~ 0.20 half lives. From equation: F=.88 T=-1.443 ln(.88)= 0.18446 = 0.1845 Range: -1.4434ln.88 =0.1845 | 1.4425ln.88 =0.18440 Age 0.1845 x 700 million = 129.2 my = 130 my
22. A volcanic rock contains zircon minerals and is present in a sequence of rock layers exposed in a cliff. A mass spectrometer analysis counted atoms of U-235 and Pb-207 in the Zircon and revealed 33% of atoms were U-235 and 67% Pb-207. 67% of the U-235 atoms decayed to Pb-207. What is the age of the zircon crystals?	P = 33% | F = 1:2 (from graph, that gives T~1.6) From equation: F=.33 T=-1.443 ln(.33)= 1.5998 Range: -1.4434ln.33 =1.6002 | 1.4425ln.33 =1.59925 Age 1.5998 x 700 million = 1,120 my = 1.12 by OR T~1.6 1.6 x 700 my = 1.12 b.y.
23. What is the age of the rock? (Is it the same as the age of the zircon crystals? Why or why not?)	Same, because zircon crystallizes as rock forms (or a few hundred years before, if it's a phenocryst)
• What do we know about the age of rocks above the flow?	Younger than 1.12 b.y.

• What do we know about the age of rocks below the flow?	Older than 1.12 b.y.
24. An igneous rock contains muscovite and is present in a sequence of rock layers exposed in a cliff. A mass spectrometer analysis counted atoms of K-40 and Ar-40 in the mineral and revealed a ratio of 1:3. (Half-life is 1.4 x 10^9 yr. – precise to 100 m.y.) What is the age of the rock?	*2 half-lives; 2 x 1.4* x 10^9 yr = *2.8* x 10^9 yr = 2.8 b.y.
25. A sedimentary rock contains a coal seam with fossils and is present in a sequence of rock layers exposed in a cliff. A mass spectrometer analysis counted atoms of C-14 and N-14 in the coal seam fossils and revealed a C-14:N-14 ratio of 1:25. (Half-life is 5700 yr. precise to 100 yr) What is the age of the coal seam?	ratio: 1:25; that's 1/26 or 0.03846 parent. From graph, that is between 4 and 5 half lives ; From equation: T=-1.443ln0.03846= 4.7014 = 4.7 Range: -1.4434ln0.03846=4.84465 | 1.4425ln0.03846=4.6999 4.7 x 5700 yr = 26,790 = 26,800 yrs
26. A zircon in a sedimentary rock has been analyzed with a mass spectrometer and found to have a U235:Pb207 ratio of 2:1? The zircon displays no chemical weathering or metamorphism. How old is the zircon?	Ratio: 2:1; that's 2/3 or 66.66668% parent. From equation: T=-1.443ln0.667= 0.5844 = 0.5844 Range: -1.4434ln0.667=0.5845 | 1.4425ln0.667=0.5842 0.5844 x 700 my = 409.1 my = 410 my
27. What is the age of the rock that contains the zircon?	Younger than 410 million years old

Relative Dating

For all the images below, order rocks from oldest to youngest. List stratigraphy in margin (youngest on top; oldest on bottom). Label, name, and include all unconformities and tilting or folding events in stratigraphy.

28. Rocks E and C are sedimentary. Faults A and F need names and orders. D is a dike. B is a granite batholith.

STRATIGRAPHY
Erosion in progress
F: Normal fault
E: Sedimentary layer
Disconformity
D: Dike
C: sedimentary layers
Nonconformity
Granite B
A: fault, unknown stress
Z: migmatite

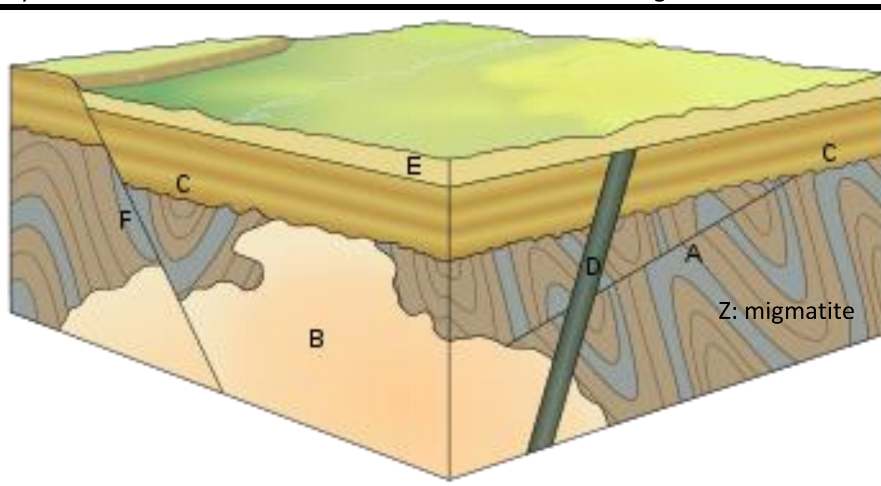


Image: Woudloper –Copyright: CC BY-SA 1.0

29.

STRATIGRAPHY
Siltstone B
Sandstone X
Conglomerate
Angular unconformity
Granite
Tilted beds
Limestone
Shale
Siltstone Q
Sandstone Y
Nonconformity
Schist

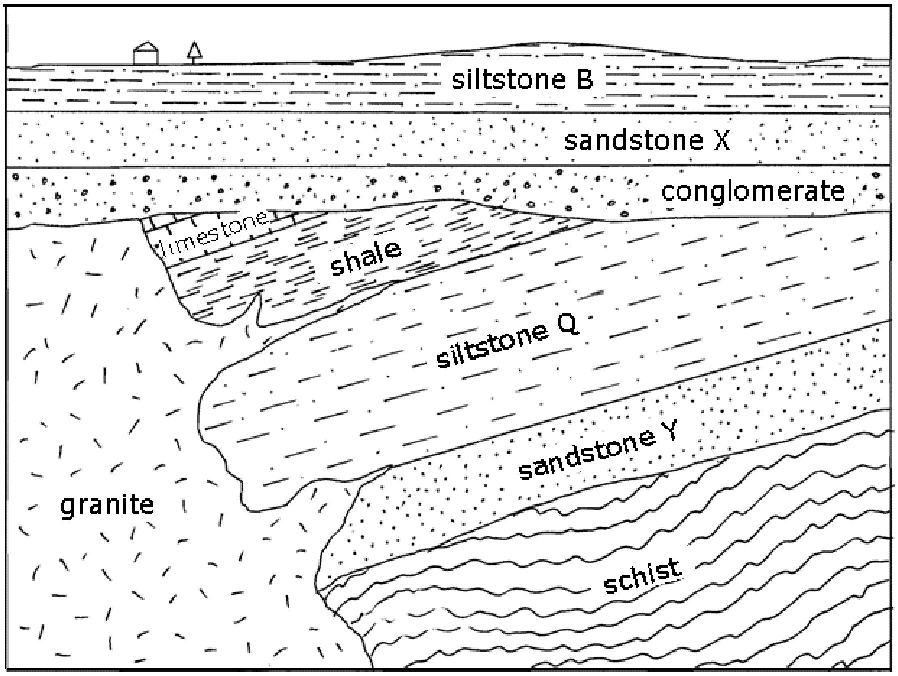


Image: Ralph Dawes and Cheryl Dawes Copyright: CC BY-SA 3.0

32. **Brick pattern** is limestone. **Point pattern** is for sandstones.
Dashed horizontal lines are for shale. Dashed lines in all directions are for a basalt dike.

STRATIGRAPHY

Soil formation and forest development
Disconformity
E: Normal Fault
D: Dike
A: Sandstone
B: Limestone
C: Shale

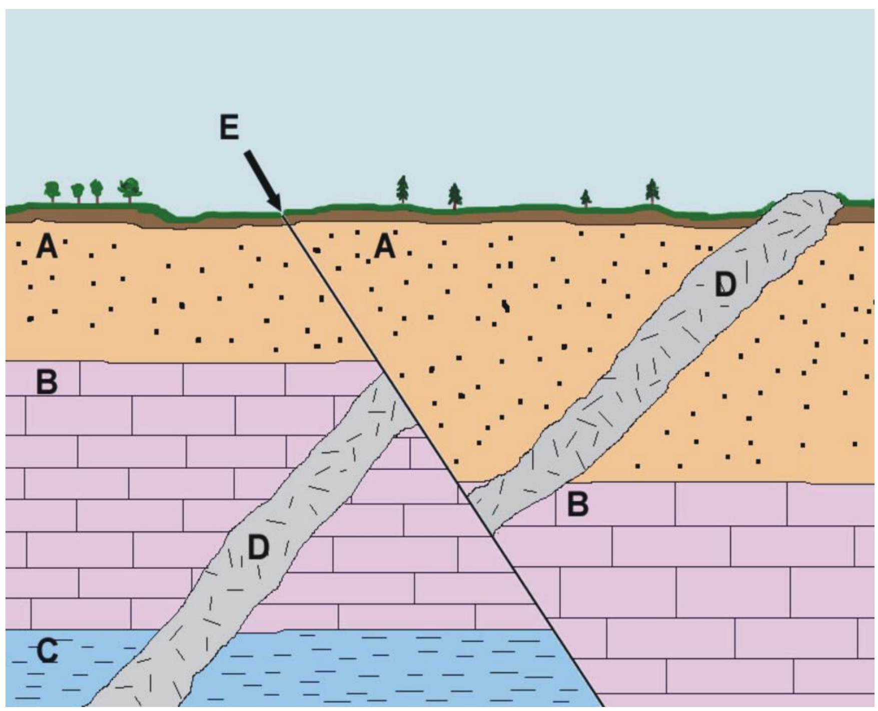


Image: Kurt Rosenkrantz Copyright: CC BY-SA 3.0

33. Do your best to recognize, name, and order different rock types in this cross-section.

STRATIGRAPHY

Erosion in progress
K. Limestone
K. Sandstone
Disconformity (surface A)
R. Dike A
R. Dike C
D. Sandstone
A. Siltstone
P. Shale
Angular unconformity (surface B)
Normal Fault
R. Dike B
H. Granite
Fold
O. Shale
L. Limestone
P. Siltstone
C. Limestone
T. Sandstone
S. Conglomerate
A. Sandstone

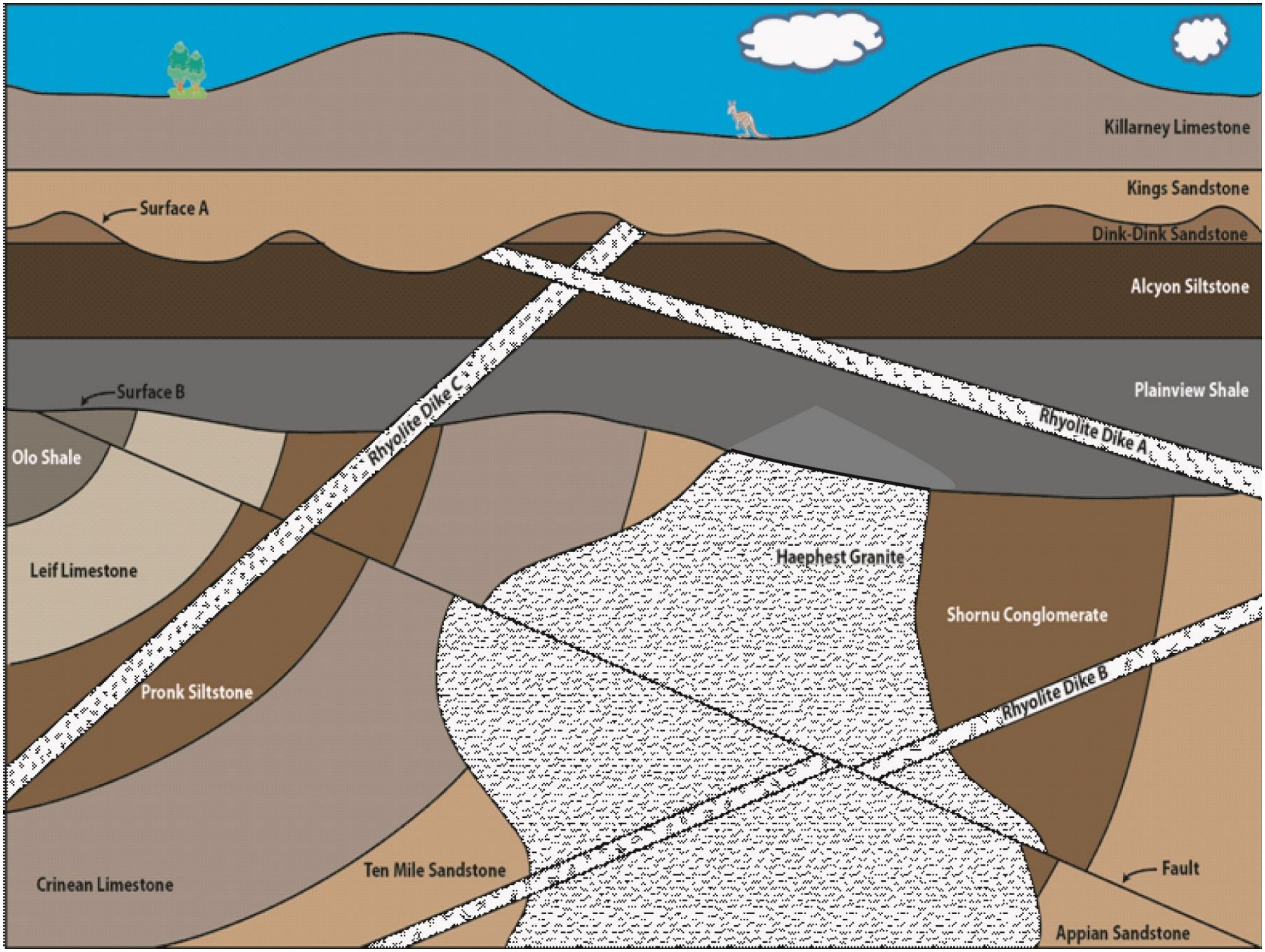


Image: Modified from one provided by Scott K. Johnson – Creative Commons – CC BY-SA 3.0

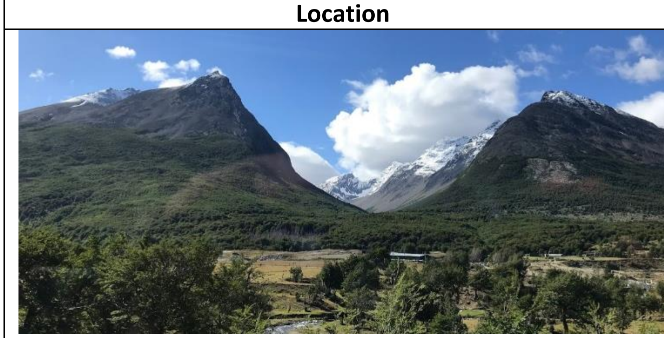
Landscapes and Geologic Maps Prereading Homework

NEEDED SUPPLIES: Protractor and Pencil and eraser

1. List the land forms you'd expect to see in an area actively impacted by the processes listed below. Reference the materials from your lecture textbook and workbook as needed.

	Depositional landforms and features	Erosional landforms and features
Coastal processes (waves, wind, and gravity and river deltas)		
Glacial processes		
Mass movement processes		
River processes		
Karst (groundwater processes)		

2. For the landscape images below, indicate which processes were the likely sculptors and what evidence tells you that:

Location	Formation processes
 Ushuaia, Argentina	
 Sierra Foothills Cave	

Landscapes and Geologic Maps Lab Exercises

INSTRUCTIONS: Use Google Earth to view in 3D the following locations and then answer the listed questions. You can use the browser version.

- Use 3D view and overhead views. For 3D, click 3D and it will fly around. Click to stop at any point.
- To get distances use the ruler.
- Use the lower-right-hand footer toolbar to see latitude and longitude and elevations.
- To get heights of objects, mouse over the object until you find the highest elevation and then do the same for lowest and subract one from other.

1. Panum Crater, CA

From USGS: "Panum Crater is a crater surrounded by an ejecta ring, with a dome in the middle. At Panum Crater the dome didn't completely fill the crater or overrun the ring (as often happens) providing an opportunity to explore all three structures. Panum Crater, part of the North Mono eruption episode, slightly preceeded the Inyo episode of 1350 C.E. and is the northernmost and youngest vent of the Mono Craters eruptions. A phreatic (steam) eruption blew out an initial crater. The material that was thrown into the air by the steam, mainly old lake bottom sediments, was deposited around the new vent in little mounds. The explosion was most likely caused by magma moving towards the surface and heating the groundwater to steam. In addition to heating anything the magma comes in contact with as it rises, the reduction in pressure during ascent causes the gas within the magma to exsolve (bubble out of the liquid), much like CO_2 comes out of a bottle of seltzer or champagne when opened. These gases drive explosive volcanic eruptions where magma is blasted out of a vent to varying heights depending on the gas pressure."

What do you notice about the shape of this crater and dome? What are its dimensions? (height, diameter)
Sketch it in profile below with scale.

What processes are primarily responsible for its formation?

CIRCLE ALL THAT APPLY: Plate Tectonics | Volcanism | Differential Rock Strength/Resistance
Erosion or deposition by Glaciers | Gravity | Groundwater | Running Water/Rivers | Waves |Wind

2. Mt. Capulin, NM

Mt. Capulin is a steep-sided volcanic cone in northeastern New Mexico, formed of cinder exploded at the time of eruption. The slope is as steep as is possible for loose material without sliding (angle of repose). A crater is in the center of the cone. A road climbs to the lowest rim of the crater. Remnants of old lava flows that accumulated on much flatter surfaces are seen surrounding the cone. These flows show a series of wrinkles indicating movement direction. This is typical of fluid lava and is known by the Hawaiian name, pahoehoe. The source of this lava may have been near the base of Mt. Capulin.

What do you notice about the shape of this cinder cone? What are its dimensions? (height, diameter)
Sketch it in profile below with scale.

What processes are primarily responsible for its formation?

CIRCLE ALL THAT APPLY: Plate Tectonics | Volcanism | Differential Rock Strength/Resistance
Erosion or deposition by Glaciers | Gravity | Groundwater | Running Water/Rivers | Waves |Wind

3. Terminal and Lateral moraines, Walker Lake, CA

On the eastern slope of the Sierra Nevada, a glacier originating in a cirque extended down the steep eastern slope to a position just at the base of the mountains. The glacier was actively eroding toward the upper portion of the divide (top of the Sierra Nevada), leaving lateral moraines (hills of glacially produced and formed unconsolidated sediment) on each side of the valley. The two lateral moraines joined as a terminal moraine at the end of the glacier.

What do you notice about the shape of the lateral moraines? What are their dimensions? (height and length from ridge divide at top to terminal moraine at base, width across from one to another) Sketch one in profile below with scale.

What processes are primarily responsible for its formation?

CIRCLE ALL THAT APPLY: Plate Tectonics | Volcanism | Differential Rock Strength/Resistance
Erosion or deposition by Glaciers | Gravity | Groundwater | Running Water/Rivers | Waves |Wind

4. **Yosemite Valley, CA –** Granite rock carved by glaciers through multiple episodes of pleistocene ice ages.
What do you notice about the shape of Yosemite Valley? What are its dimensions? (height, length, width) Sketch it in profile below with scale.

What processes are primarily responsible for its formation?

CIRCLE ALL THAT APPLY: Plate Tectonics | Volcanism | Differential Rock Strength/Resistance
Erosion or deposition by Glaciers | Gravity | Groundwater | Running Water/Rivers | Waves |Wind

5. **Rock Islands, Palau | Ha Long Bay, Vietnam | South China Karst --** a collection of limestone islands or hills.
What do you notice about the shape of these landscapes? Pick a hill or island: what are its dimensions? (height and diameter). Sketch one in profile below with scale.

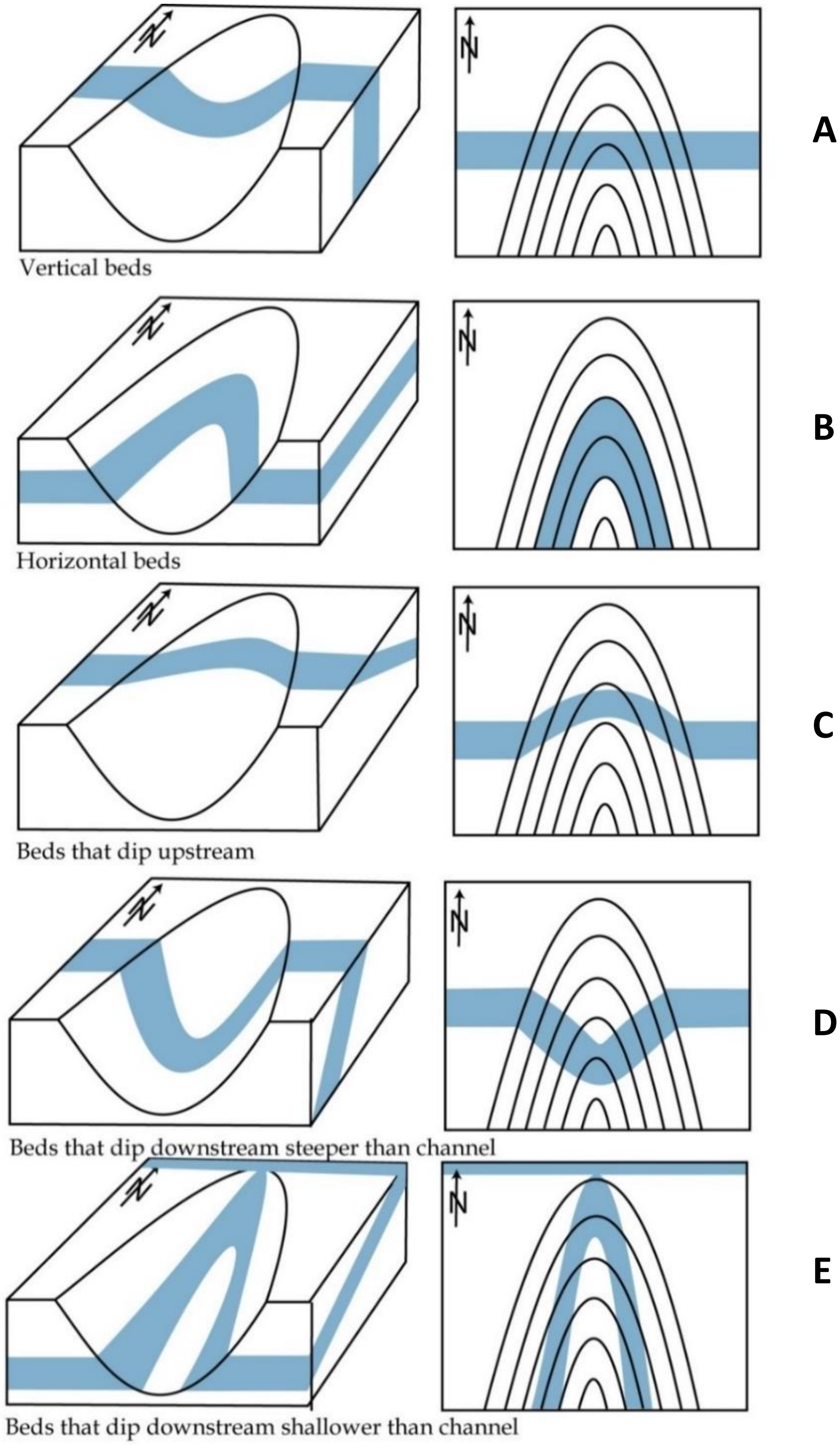
What processes are primarily responsible for its formation?

CIRCLE ALL THAT APPLY: Plate Tectonics | Volcanism | Differential Rock Strength/Resistance
Erosion or deposition by Glaciers | Gravity | Groundwater | Running Water/Rivers | Waves |Wind

GEOLOGIC MAP REVIEW:

6. For the images below, note that block diagrams shown is an excavated canyon, and the map views show contour lines of the canyon. On each **map view**, add an attitude marker that corresponds to the shaded rock shown (give best estimates for angles for beds that are not vertical or horizontal, as you cannot use a protractor).

BLOCK DIAGRAM **MAP VIEW**



7.	If, on a flat surface, you see a horseshoe-shaped rock outcrop pattern open to the south, and the beds are dipping away from the center, what kind of structure are you observing? (Be as thorough as you can!)
8.	Where do you find the oldest rocks on the surface of such a fold?
9.	When interpreting geologic maps, it helps to remember that contacts between horizontal beds are parallel to contours. Which block diagram on the previous page of the prereading demonstrates that?

Geologic Map of the Athens Quadrangle, Tennessee (map only – not the cross-section) NOTE: This map is also available in electronic form on the class website.

10.	What is the dominant geologic structure under the Red Hills? (use strikes and dips of similar beds to figure it out.) Give FULL name.
11.	What is the dominant geologic structure around the town of Mashburn? (use strikes and dips of similar beds…) Give FULL name.
12.	The youngest rock in the area is Oo – Ottosee Shale. Look along cross-section line A-A' and find this rock type. What geological structural feature is it part of and what part of it does it appear in (center or sides)?
13.	Oh or Oo -- which bed in this structure appears more resistant to erosion? What's the evidence?

Geologic Map of the Grand Canyon NOTE: This map is also available in electronic form on the class website.

14.	There is a topographical (NOT structural) basin in the central top of the map – (labeled basin). What rock unit/bed is exposed in the center of the basin?
15.	How do we know for sure that this region is a topographical (erosional) basin – as opposed to a structural basin (here in the Grand Canyon only)? (Sketch a cross-section across the basin – showing topography AND geology – beds.)
16.	List below the rocks that are found at the highest elevations on the edges of the Grand Canyon itself. Provide its name, unit color for legend, and attitude (strike and dip).
17.	Use the legend to find the color and name of the oldest rock visible in the bottom of the canyon. What its name, color, and rock type? Where is it found? (What section of the canyon?)

18. Virtual Field Trip: Go to class website, and click the link for the virtual field trip to the Grand Canyon. Explore for about 5 minutes. What are your thoughts about traveling to the Grand Canyon and exploring in person?

Geologic Map of California – Use online website link: Zoom into San Francisco

19. What is the strike of the San Andreas Fault south of San Francisco?	20. What is the strike of the um rocks (purple) that cross San Francisco?
21. If similar strikes, why? If not, why not?	
22. What is the width in kilometers of the San Andreas Fault system in the San Francisco Bay Area? (The San Andreas fault is actually a system of parallel right-lateral strike-slip faults. Look for the strike-slip fault that's most westerly and the one that's most easterly and measure the distance between them. This is the width of the San Andreas Fault system.)	
23. Look at the rock types present in the Sierra Nevada (mountains that run along the eastern edge of the state). What is the symbol and color that represents the most common rock found in the Sierra Nevada (the batholith)?	
24. The southern edge of the Sierra Nevada has been sliced off by the San Andreas and Garlock faults and carried north over the past 25 million year (on the west side of the San Andreas Fault -- the side that moves north). What is the location of the furthest place north these have been moved?	
25. Where’s the place closest to San Francisco that you can seek some of this material?	
26. What rock type exists under your house or apartment? Structures (faults, fold, etc)? Look for strike and dip symbols or nearby fault or fold axes. If you don't see any near you then find closest and note what it is and how far away.	

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

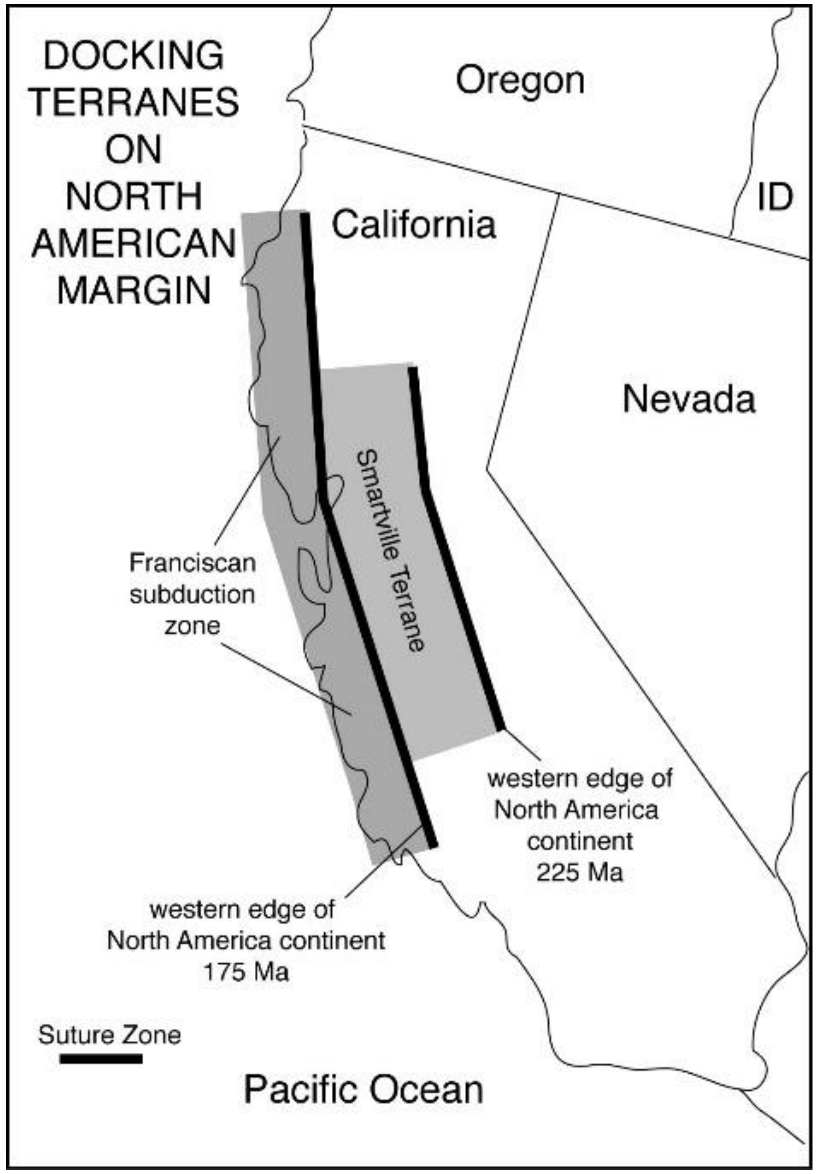
Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Evalaute and classify in the landscape depositional and erosional landforms and the processes that form them	A | B | C | D | F	
Compare and contrast topographic and geologic features found collectively on a geologic map	A | B | C | D | F	
Describe the general geologic features found across the landscape of California and the Grand Canyon.	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

San Francisco Geology: Franciscan Assemblage

For much of the past 500 m.y. the west coast of North America was a subduction zone. The lower portion of the subducting plate descended into the mantle and was assimilated. The upper portion, however, was scraped off in slivers and accreted. From 375 Ma to 225 Ma, the Sonomia terranes accreted to the North American continent, plugging up the subduction zone and moving it (and the continental margin) about 100 miles westward.

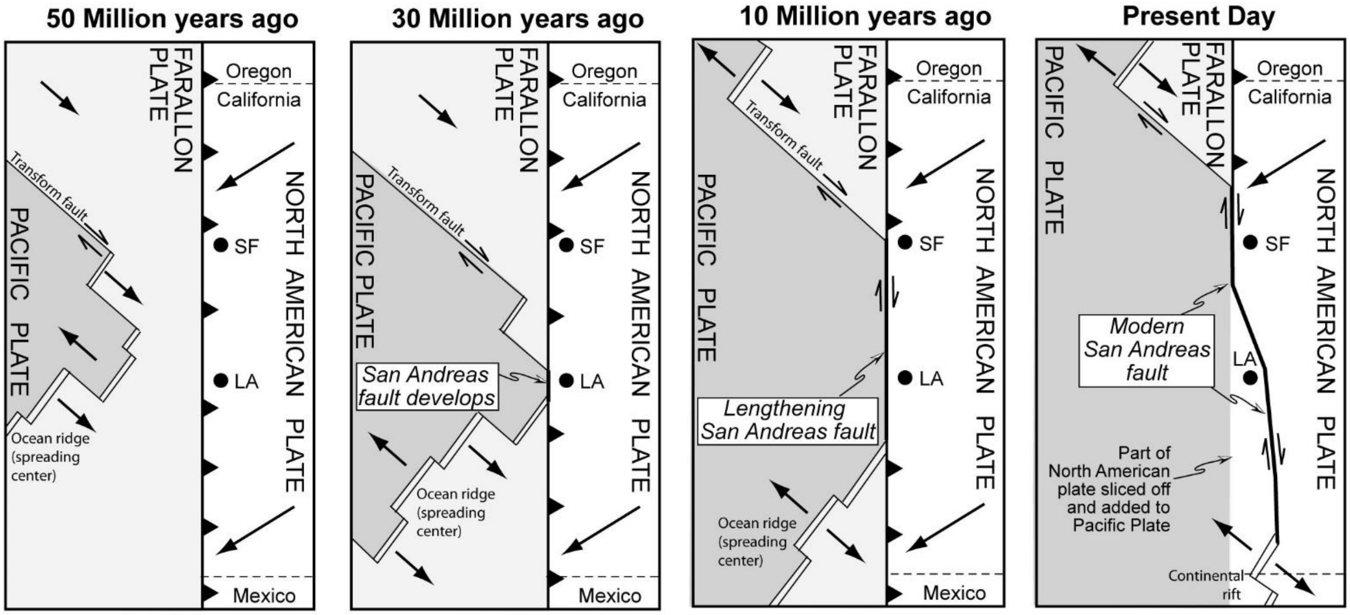


About 225 Ma, the western edge of the North American plate was near the present-day Sierra Nevada foothills. For 50 m.y., the Smartville terranes accreted, again plugging up the subduction zone and moving it farther west.

Around 175 Ma, the Franciscan subduction zone formed, and for 140 m.y., the Franciscan Assemblage terranes accreted along the North American continental margin.

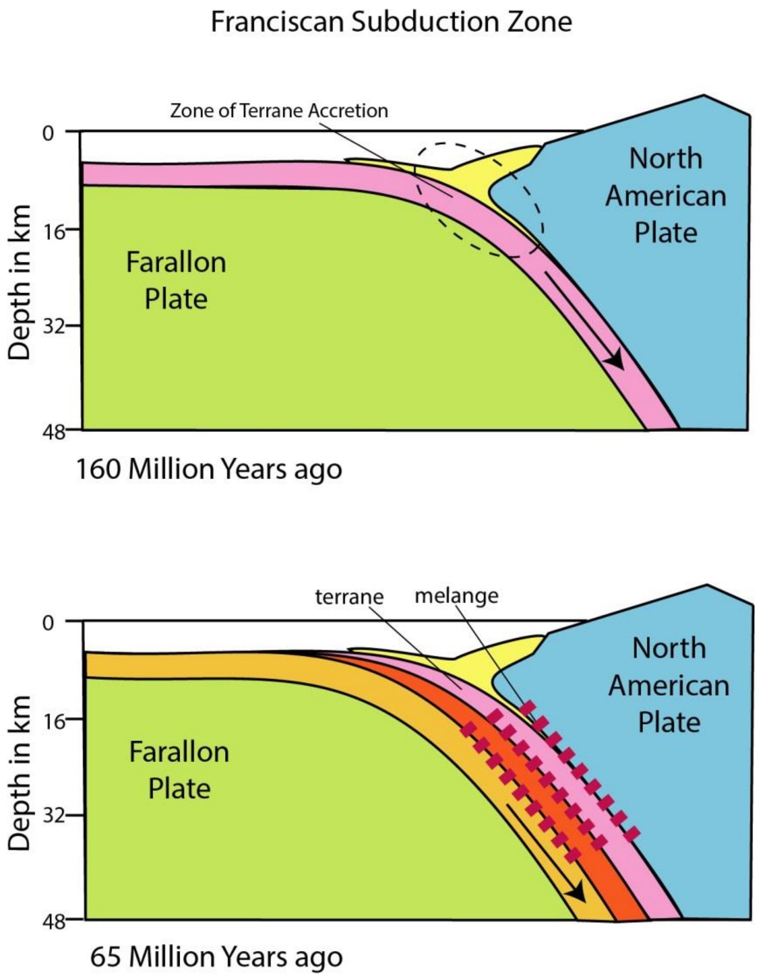
During the Franciscan accretion, tens of thousands of feet of rocks accumulated in the subduction zone and accreted to the continent in successive near-vertical slivers that extended up to 30 miles below the surface. Continental sediments moved into the offshore trench and were themselves caught up in the accretion process. By 65 Ma, much of the Farallon plate was entirely subducted: the North American plate was now overrunning the spreading center that separated it from the Pacific Plate. The plate boundary began changing to a transform plate boundary between the Pacific and the North American plates.

Image: Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, no. 12, p. 3513-3535.

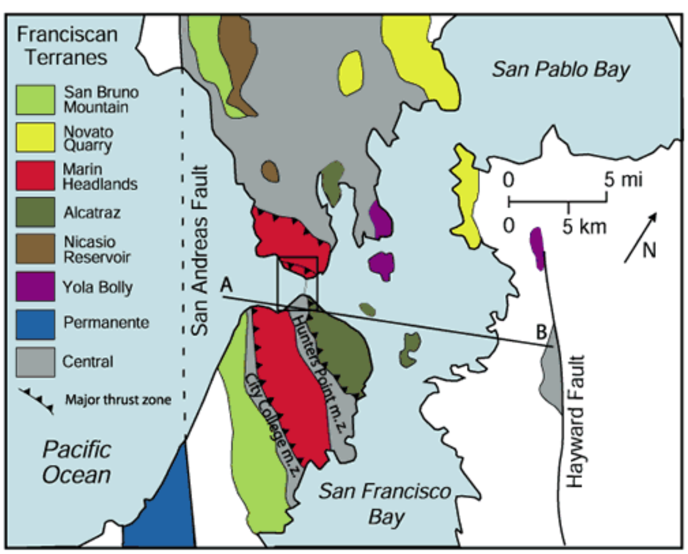


From 140 m.y. the Farallon plate moved eastward into the Franciscan subduction zone during which time the Franciscan Assemblage formed. The East Pacific Rise spreading center also moved eastward and at ~30 Ma the ocean ridge entered the subduction zone at the latitude of Los Angeles. Consequently the San Andreas fault began to form due to oblique divergence between the North American plate and the northward-migrating Pacific plate.

For the next 20 m.y. (30-10 Ma), continued subduction of the East Pacific Rise caused the San Andreas fault to grow in length toward the north and the south, and by ~10 Ma the San Andreas fault had reached the latitude of San Francisco. Over the next 10 m.y. the San Andreas continued to lengthen and stepped eastward near Los Angeles slicing of a part of the North American plate. This former piece of the North American plate is now a part of the Pacific plate and moves northward at a rate of 2 in/yr.



Terrane accretion along the Pacific continental margin. Note that the mélanges are the shear zones formed between terranes.



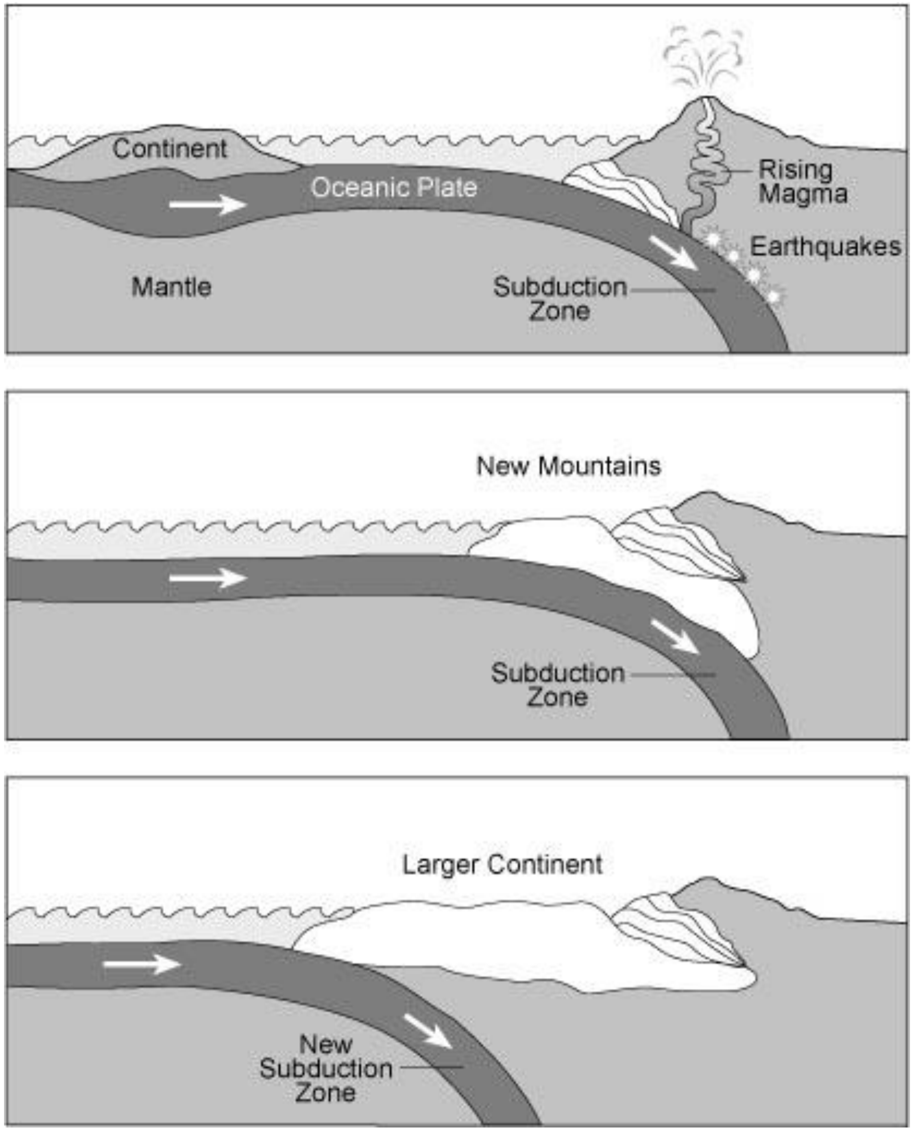
Geologic Map of the San Francisco Peninsula.
Image: Will Elder, NPS

The Franciscan rocks in San Francisco consist of five distinctly different terranes (or mélanges) that accreted one after the other. As the Farallon plate subducted under North America, it would periodically either get scraped off or stuck and broken off. That portion of the subducting plate would then become part of the North American plate (accretion). The subduction zone would move westward and begin subducting under the newly accreted margin of North America. In such a manner, each terrane was progressively shoved under the preceding one, and the North American margin moved westward.

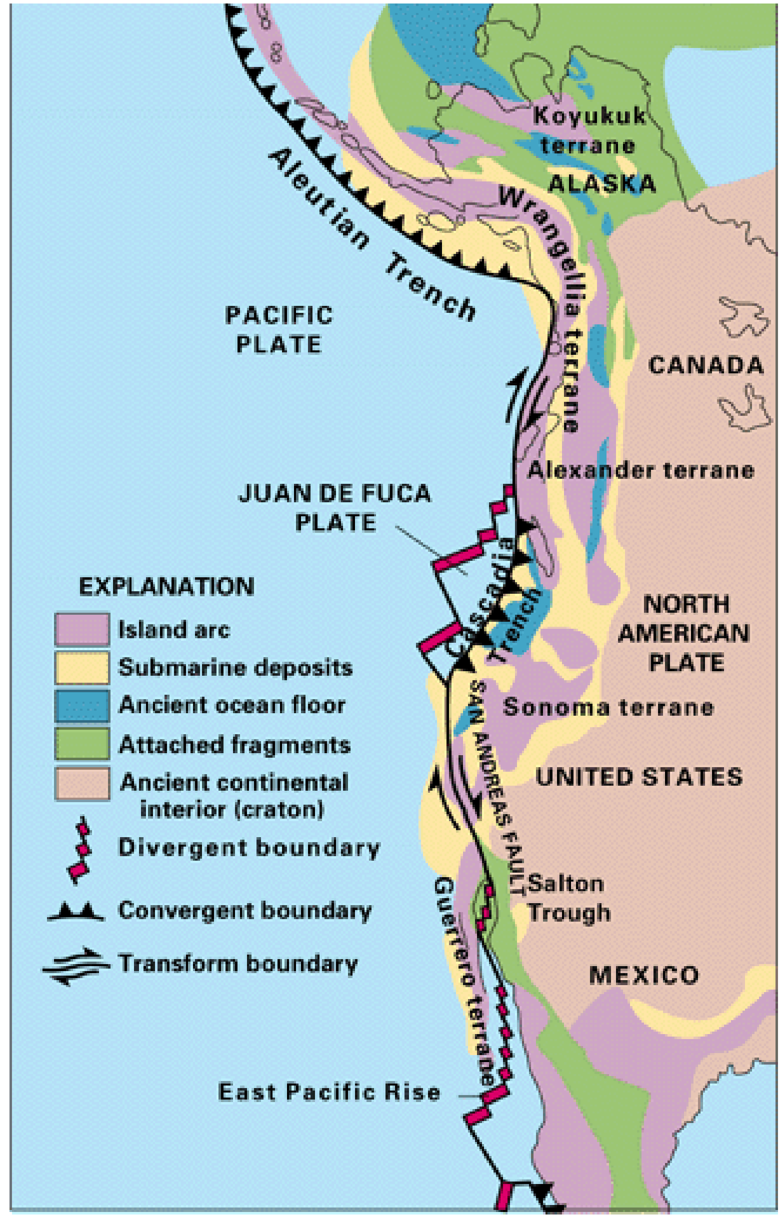
The boundaries between terranes are called shear zones and are the formation location for melanges; they display textures and mineralogy associated with the results of severe shearing as one terrane was thrust against another.

The Franciscan subduction zone stopped 65 Ma. 25 Ma, the San Andreas fault system developed to accommodate the transform motion connecting the seafloor spreading centers off Northern California and in the Gulf of California. Since 65 Ma, the region has been slowly uplifting and eroding, exposing the Franciscan rocks at the surface. Now we see the top edges of these terranes (slivers that still extend to great depths below us). These edges appear as parallel stripes that run diagonally northwest across the city.

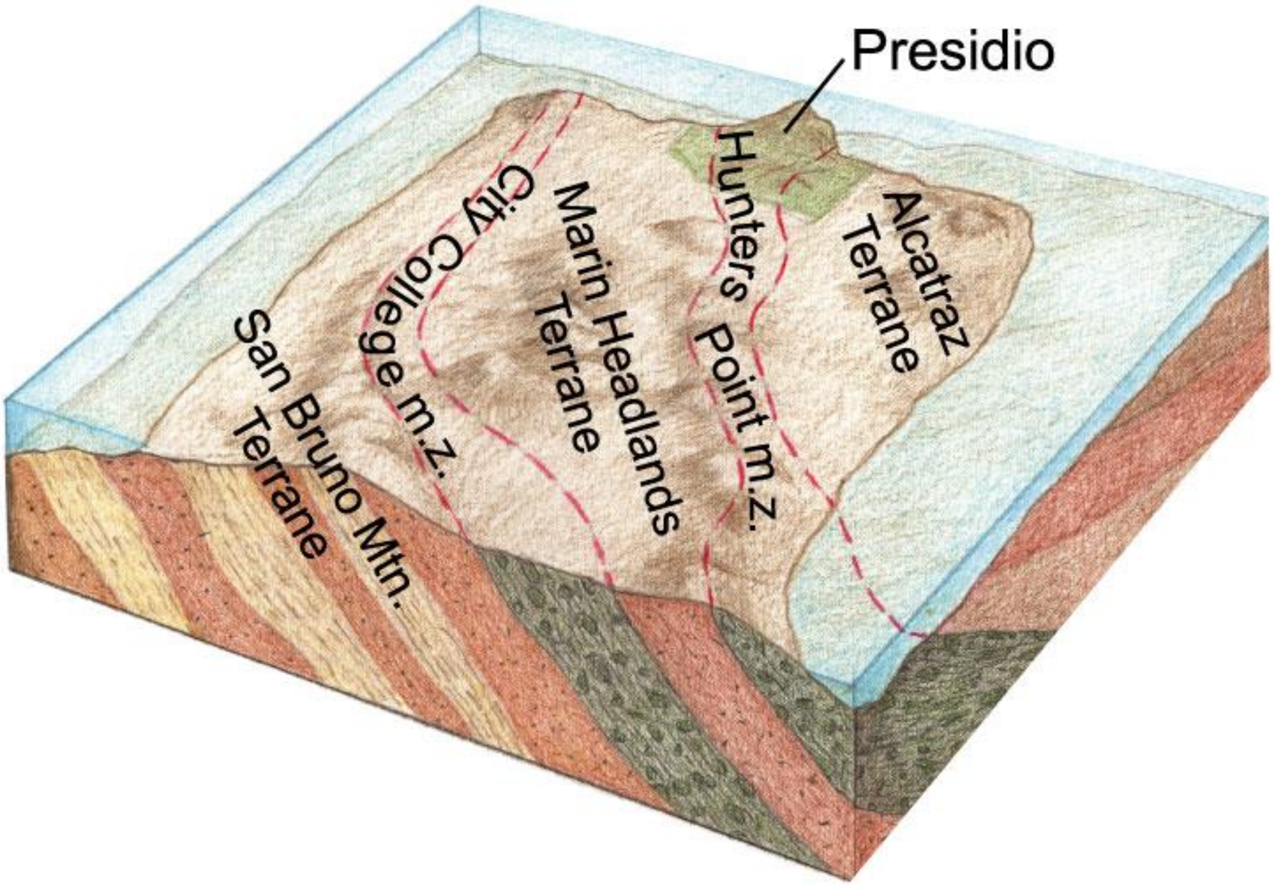
Because of their accretion order, the slivers farther inland are the oldest; the ones closer to the plate boundary are the youngest. (Imagine a stack of pancakes tilted parallel to the angle of the subducting oceanic plate. The oldest pancake – first one accreted – is on top!)

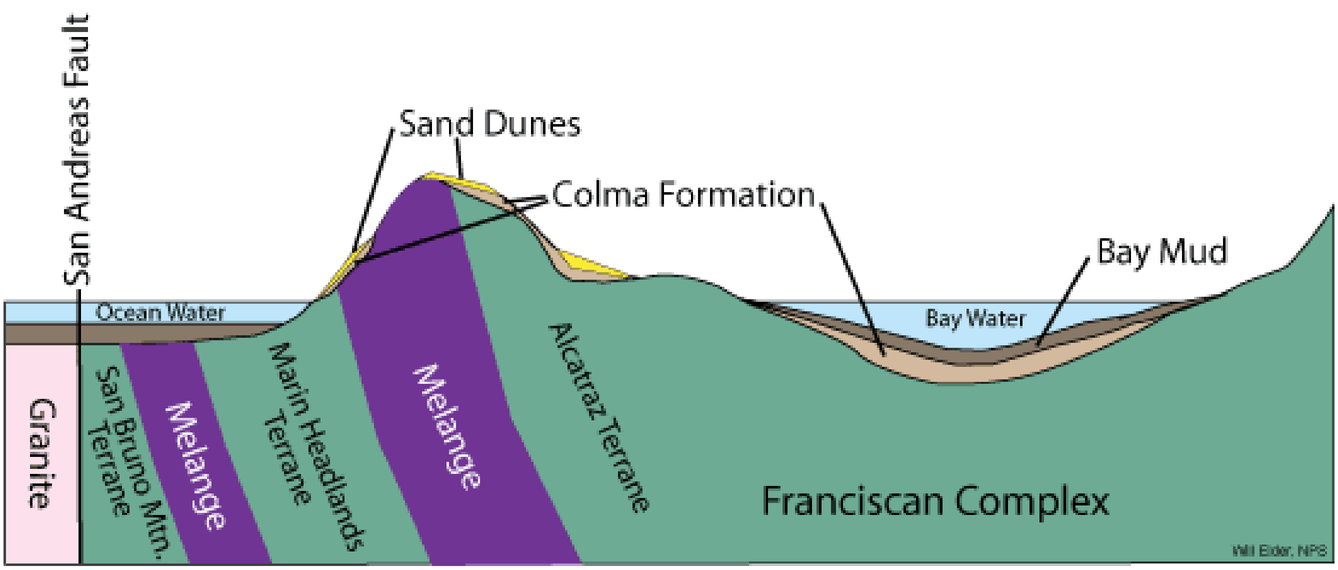


Terrane accretion. Image from Kenneth R. Lang's book
The Cambridge Guide to the Solar System, Second Edition 2011.



Terrane accretion along the western margin of North America. USGS.





Top picture: 3-D block diagram showing the major bedrock formations underlying San Francisco. Bottom picture: cross-section from west to east looking North across the San Francisco Peninsula. Note the sand and mud that covers much of the low-lying areas. Images from: Will Elder, National Park Service

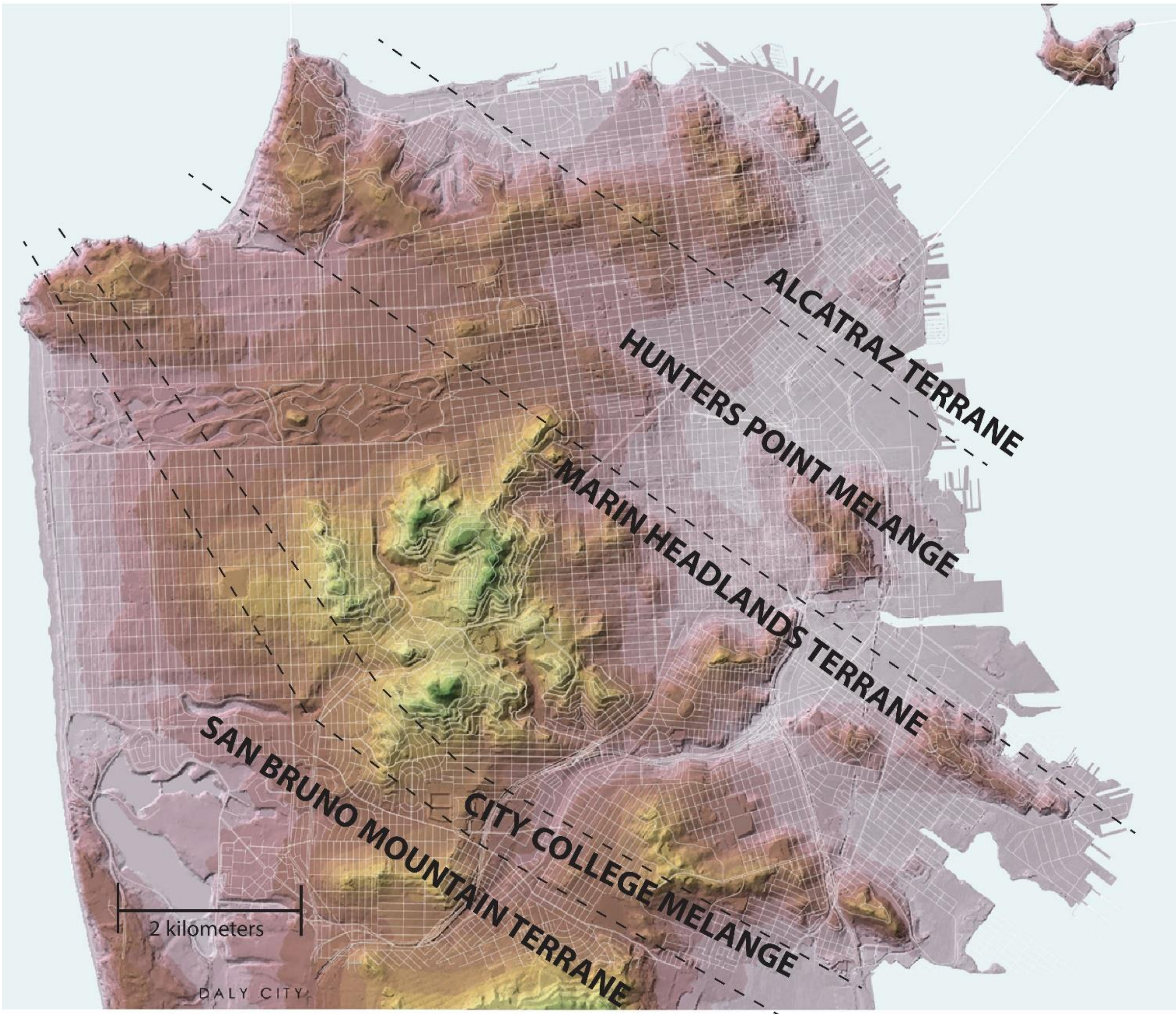


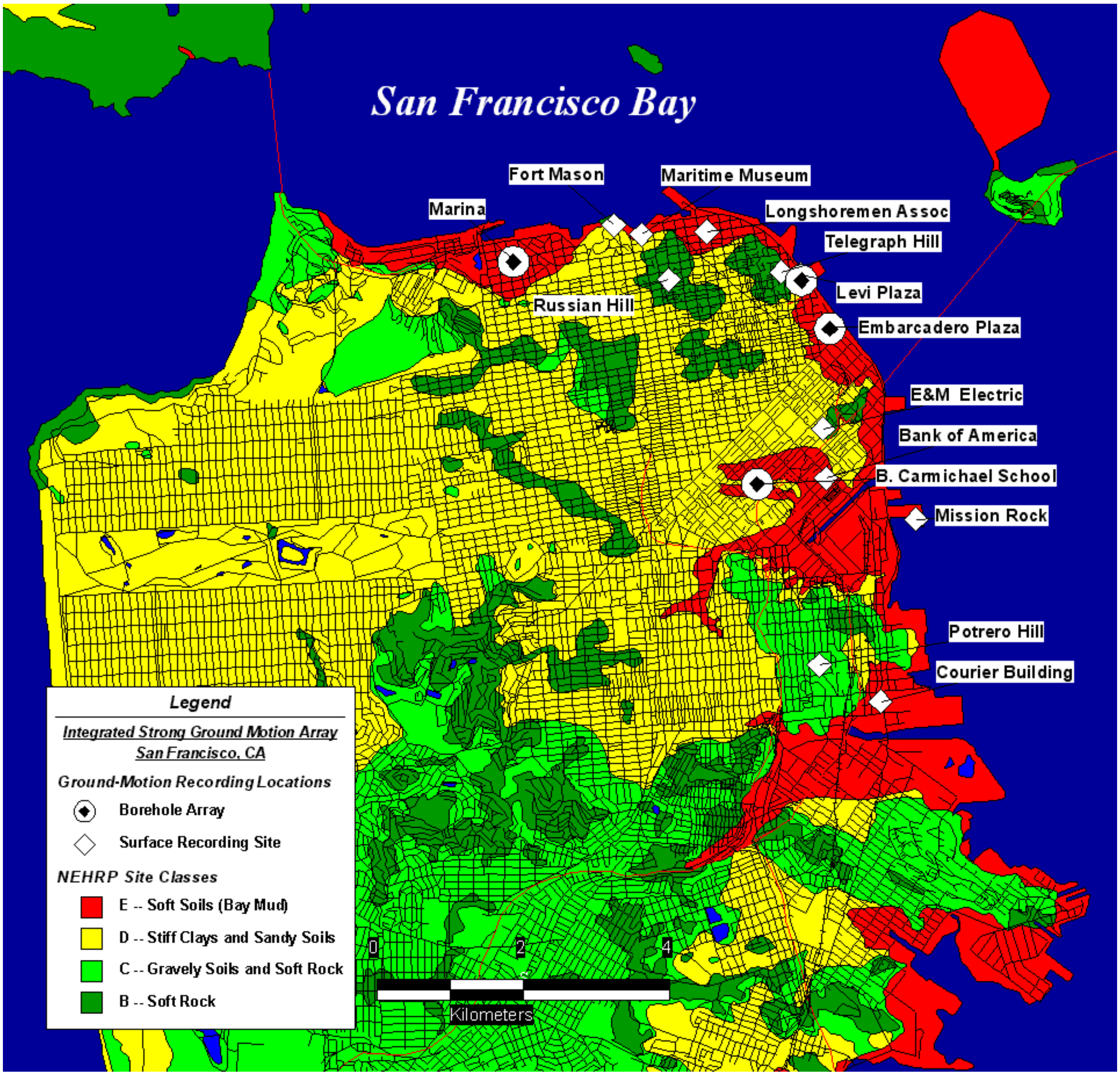
Image: Simplified terrane map of San Francisco. Everything in this image that is not a hilltop is either covered by sand (most of the west and northern regions) or bay mud/fill (most of the eastern coastal edges of San Francisco). The hilltops stick out above these sediments and provide a location where we can peek into the underlying bedrock.

Five Franciscan Assemblage terranes/mélanges that you find around San Francisco (listed in order from oldest to youngest):

1. **Alcatraz Terrane** – Thick-bedded sandstone. Grains were derived from many different rock types eroded along the North American continental margin and carried by rivers to the ocean and into the trench by turbidity currents (avalanches of sediment) down submarine canyons (deeply carved features that extend off the continental shelf). Transportation, deposition rapid.
2. **Hunters Point Melange** – Large blocks of serpentinite in soft clay and serpentine matrix. Formed along the zone of thrusting between the rocks of the Marin Headlands terrane and the Alcatraz terrane, while those rocks were in the subduction zone. Serpentinite forms at a spreading center where mantle rocks are altered by hot seawater that reaches the deep rocks through cracks formed during spreading. (Serpentinite forms the lower part of the earth's oceanic crust worldwide.) Small isolated blocks represent pieces of oceanic crust that were broken up and squeezed upward through the overlying host rock like watermelon seeds.
3. **Marin Headlands Terrane** – Pillow basalt, red chert, shale, and sandstone, typically in thin fault slices. Record of the 100 m.y. migration of mid Mesozoic Pacific Ocean floor from its eruption, close to the equator, on a spreading ridge, to its accretion by subduction thousands of km to the northeast. Pillow basalt overlain by ribbon chert (hardened silica-shelled muds, formed when planktonic silica-shelled organisms die, and their shells slowly rain down to the

ocean floor (1 cm/1000 yr) and collect over time), overlain by turbidity-current-transported sandstone of continental origin, deposited just prior to accretion.

4. **City College Melange** – Blocks of basalt, chert, serpentinite, schist, gabbro, and sandstone in soft clay and serpentine matrix. Formed along the zone of thrusting between the rocks of the San Bruno Mountain terrane and the Marin Headlands terrane, while those rocks were in the subduction zone. The rocks are thoroughly ground up by thrusting. Blocks in the mélange are pieces of hard rock that survived grinding.
5. **San Bruno Mountain Terrane** – Sandstone with interlayered mudstone in places. Grains were derived from many different rock types eroded along the North American continental margin and carried by rivers to the ocean and into the trench by turbidity currents (avalanches of sediment) down submarine canyons (deeply carved features that extend off the continental shelf). Sand and seafloor mud in layers.



Ground shaking map – USGS. Note the yellow areas are mostly ice age sand dunes. The red is bay mud/fill added to the edges of San Francisco to increase its land area. The green are the rocky outcrops of the various terranes.

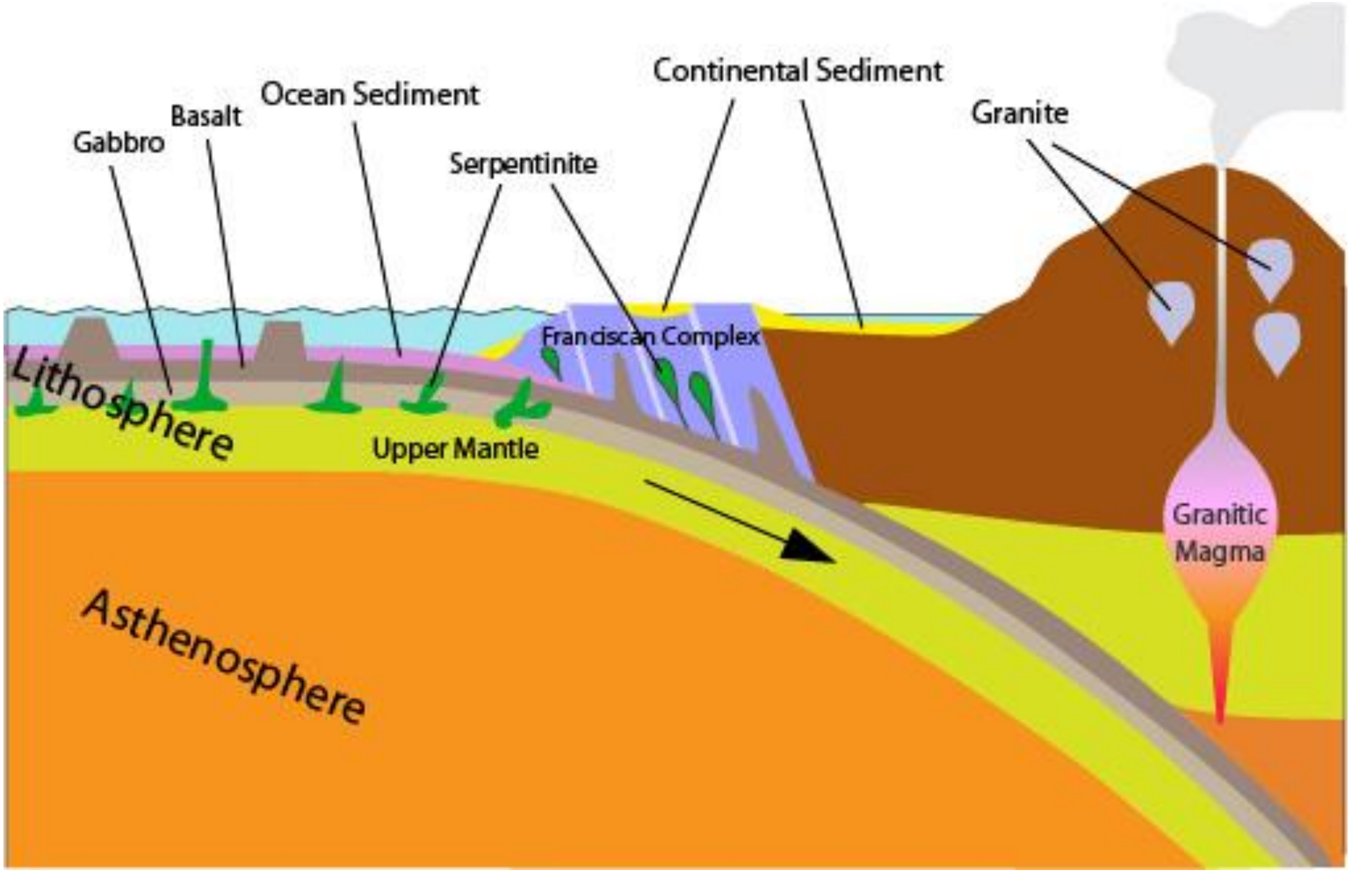
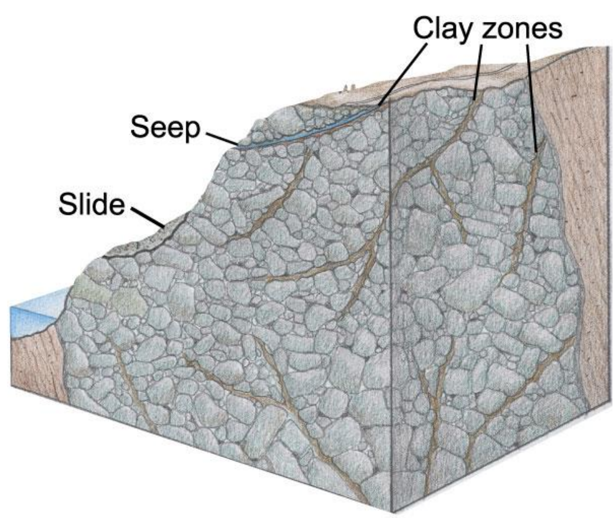


Illustration of the processes involved with bringing Franciscan rocks to California as part of subduction, and the subsequent transfer of these rocks to the continent (scraped off) to become terranes. Image: Cort Benningfield,

Melanges

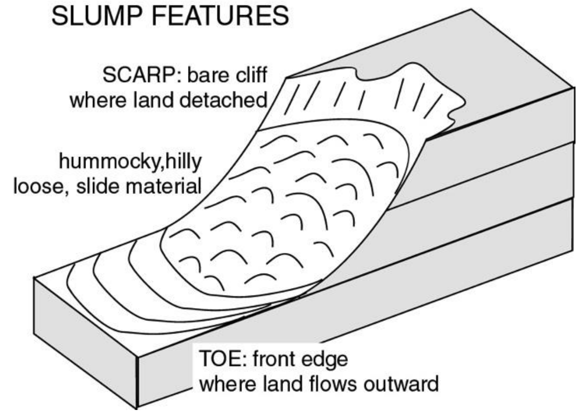
Melanges are common in the Northern California coast ranges: recognized by large random boulders sitting on rolling hillsides. Boulders are hard and stand out from the soft greenish-gray or bluish-gray clay matrix, which is seldom seen. The clay matrix does not have layering. Melanges form because intense shearing in the subduction zone reduces the hard rocks to a sheared paste. Landslides are common where mélange occur on steep slopes.

The Hunters Point Melange is known for its serpentinite. (rock composed entirely of the mineral serpentine). Soils formed from serpentine are characterized by anomalous plant life, due to the composition of serpentine: Fe and Mg silicate. There is almost no Al, so no clay soils are formed, and the soil is thin and gravelly. The serpentine also has toxic amounts of Mg, Ni, Cr, and Co, and is low in plant nutrients such as K, Na, Ca, and P.



SERPENTINITE underground:
Image: Will Elder, NPS

Most common plants avoid serpentinite, but a few hard and specialized plants thrive under these conditions: including Tiburon Indian Paintbrush, Oakland Star Tulip, and the very rare Tiburon Mariposa Lily (~2 ft high and blooms in May and June with cinnamon and yellow flowers).



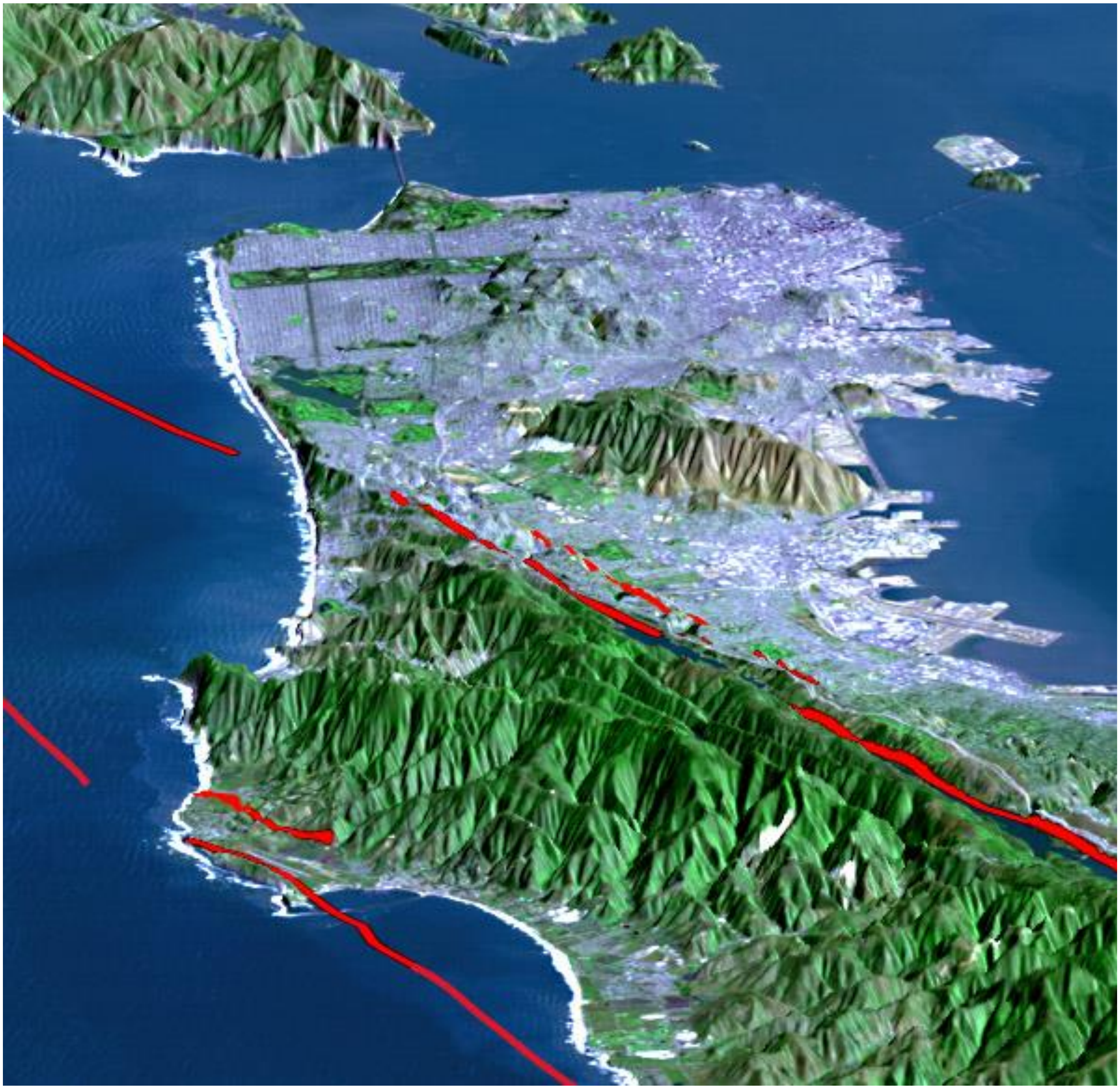
On fresh exposures, the rock is pale green, sometimes with dark specks about the size of small peas. These dark specks are remnants of pyroxene crystals that have been altered to serpentine. In places, some large blocks of this serpentinite have broken off and are slowly sliding down hillsides, lubricated by the soft and slippery clay of the underlying mélange. Rainwater accumulates in fractures in the serpentinite and makes its way down to the contact with the clay. Putting water along this contact zone is like putting wax on the bottoms of skis. The fine clay matrix holds water near the surface and is quite slippery when wet. The clay flows downhill, taking roads, buildings, and whatever else has been built on the mélange.

Many homeowners think that if they build their homes on solid rocks, they'll have little chance of a landslide. But the solid rocks in mélanges are really just boulders surrounded by a clay matrix. And if the boulder is serpentinite, it will hydrolyze quickly and get weak when in contact with surface water.

About 65 Ma, the tectonics of the California coastline between Northern California and Baja California began a radical change. Prior to that date, it was a convergent plate boundary, with an active subduction zone. But about 65 Ma, the subduction zone plugged up with sediment from the accretionary wedge and the subduction of an active spreading center. Over the next 35-40 m.y., a transform fault boundary arose. This new plate boundary developed into the San Andreas fault system (SAFS) about 25 Ma.

Recent history
Once the subduction zone disappeared, the coastal rocks began to uplift, because there was no longer a force pulling downward into a subduction zone. The crust pushing upward created an early version of the coastal mountain chain. For the past 5 m.y., while uplift has occurred along the California coast ranges, the area around San Francisco Bay has been an anomaly – subsiding and letting the Pacific Ocean flood into the Sacramento River to form San Francisco Bay. The tops of some of the older hills became islands, such as Alcatraz and Angel Island.

The San Andreas fault trace leaves the coast at Mussel Rock south of Fort Funston.
It hits land again north in Bolinas, where it cuts across Point Reyes and then goes back to sea. *(Image: USGS)*



Notice that the region around San Francisco Bay is uplifting (mountainous), while the Bay itself is subsiding. *(Image: USGS)*

San Francisco Geology Prereading Homework

1. When did the Franciscan subduction zone begin and end?	2. When did the San Andreas Fault System originate?
3. What happened to the North American margin during the Franciscan?	
4. Why did the San Andreas fault system develop?	
5. List the Franciscan terrane/mélanges in order from youngest to oldest:	
6. **Where and how** did the sandstones in the Franciscan form?	
7. Which two terranes/melanges contain **mostly** sandstone?	
8. **Where and how** did serpentinite in the Franciscan form?	
9. Which two terrane/melanges contain **large amounts of** serpentinite?	
10. What's a mélange and how do they form?	
11. What's the biggest hazard of a mélange? Why? How would you explain the hazards of mélanges to local homeowners? (They think that if they build their homes on solid rock, they'll be fine.)	
12. **Where and how** did the Marin Headlands terrane form?	

San Francisco Geology Field Trip Exercises

Stop 1 – Sutro Baths Tunnel Entrance – Cliff face

The San Bruno Mountain terrane is a sequence of interlayered sandstones and mudstones. The sandstone is more massive. The mudstones are mostly thin lenses. There are places along the bottom of the exposure where clear rip-ups have occurred by turbidity currents that formed these deposits. **CHALLENGE**: Find a place that shows both the sandstone and the mudstone. And locate the rip-ups. Draw a picture of the contact and the two main rock types. Show textures. Label each rock type and feature, including the rip ups. DON'T FORGET SCALE.
CHALLENGE: Find an area with a large number of fractures, and draw a picture below. Label rock types and features. DON'T FORGET SCALE.
CHALLENGE: What kind of stress formed these fractures? (Circle: Compression, tension, or shear) What was the most likely source of that stress?
CHALLENGE: When you're done, while waiting, go into the tunnel and find the cave. Explore it a little and see if you can figure out how the tunnels and cave formed.

Uphill behind Sutro Baths

As we walk above Sutro Baths, we will reach a level surface, called a marine terrace. These features form when sea level drops and/or land uplifts, placing old wave-cut platforms (beaches) above current ones. **CHALLENGE**: What evidence can you see around this area to prove that it was once the beach?

As we continue our walk, we will move from the San Bruno Mountain terrane into the City College mélange. Watch closely to see the change in rocks – mostly visible through rock chunks in soil.
CHALLENGE: Where specifically do we cross from San Bruno Mountain terrane to City College mélange? (Give approximate location relative to known parts of the trail.)

CHALLENGE: How did we know? (Evidence…)

Trail in the middle of the landslide behind Sutro Baths

CHALLENGE: Describe the serpentinite soil: Grain size, texture, color, and other observations.

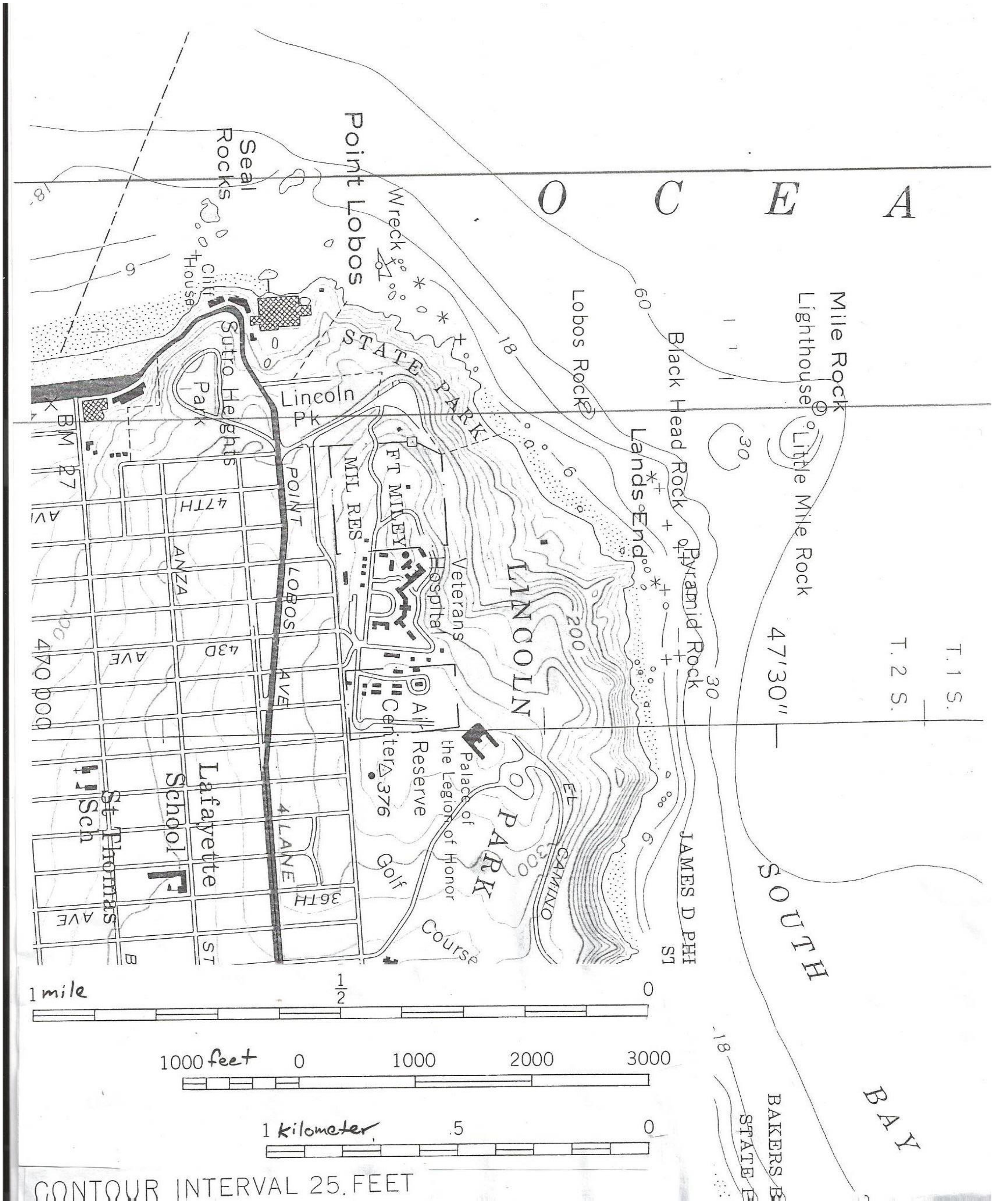
Landslide overlook (under golf course access road)

As we walk along the coastal trail through the City College mélange, we are also walking across a massive landslide, right under the Veterans Hospital, behind the Legion of Honor. The landslide was caused by wave action undercutting the City College mélange. In the early 1880s, a rail line used this same route to take people between downtown and the Cliff House. It was abandoned because of the huge maintenance costs resulting from the unstable roadbed.
CHALLENGE: What is the approximate size of this landslide (height, width, depth)?

Base of headland to north of landslide behind Sutro Baths

As we walk down to the beach, we will see various solid rock blocks that can be found in the City College mélange – serpentinite, chert, schist, and a spectrum of other metamorphic rocks that form in the high pressures and moderate temperatures associated with subduction zones. Some rocks here are riddled with veins of a special type of serpentinite, similar to asbestos. **CHALLENGE:** Find one large beach cobble and sketch and characterize it: texture, scale, color, features, etc.

Sketch (close up – include scale)



Topographic map of Lands End. (From USGS map.)

Weekly Reflection

Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Describe the general geologic history of San Francisco	A | B | C | D | F	
Evaluate the formation environments and relative ages of rocks and materials found in San Francisco	A | B | C | D | F	
Make careful field observations	A | B | C | D | F	

INSIGHTS

What new insights have you developed this week due to the week's content? Did anything in particular help you understand something you've always wondered about, or made you think about the world with new eyes?

San Francisco Geology Field Trip Practice Sheet

1. During the Franciscan time period, what was happening, geologically, in the Sierra Nevada Mountains?	
2. What was happening in the area we know today as San Francisco?	
3. When did the Franciscan begin?	
4. Why did the Franciscan end?	
5. When did the Franciscan end?	
6. What major California feature formed after the Franciscan?	
7. How old is this feature (for how long has it existed in close to its present form)?	
8. List the Franciscan terranes/mélanges in order from the one first accreted to the one most recently accreted.	
9. Which Franciscan terranes/mélanges contain significant amounts of sandstone?	
10. In what environments were those sandstones deposited originally?	
11. Which Franciscan terranes/mélanges contain serpentinite?	
12. How does serpentinite form?	
13. How did the serpentinite get where it is now?	
14. Which Franciscan terranes/mélanges contain chert and basalt?	
15. How did these rocks form?	
16. What is the formation process of a mélange?	
17. What is its biggest hazard associated with building or living on mélanges today?	
18. At Sutro baths, you observed sandstones and mudstones of the San Bruno Mountain Terrane. What was the original depositional environment of these rocks?	
19. Up the hill behind Sutro Baths, we reached a level marine terrace. What evidence supported this contention?	
20. Farther above Sutro Baths, we reached the City College Melange. What were some of the rocks in this mélange?	
21. Later we saw a landslide. Why was it there? What contributed to its formation?	

KEY

1. During the Franciscan time period, what was happening, geologically, in the Sierra Nevada Mountains?	Volcanism associated with subduction. The Sierra Nevada were, then, an active volcanic arc.
2. What was happening in the area we know today as San Francisco?	Terrane accretion in a subduction zone.
3. When did the Franciscan begin?	175 Ma
4. Why did the Franciscan end?	Offshore seafloor spreading center began to subduct.
5. When did the Franciscan end?	~65 Ma
6. What major California feature formed after the Franciscan?	San Andreas fault
7. How old is this feature (for how long has it existed in close to its present form)?	~25 Ma
8. List the Franciscan terranes/mélanges in order from the one first accreted to the one most recently accreted.	Alcatraz, Hunters Point, Marin Headlands, City College, San Bruno
9. Which Franciscan terranes/mélanges contain significant amounts of sandstone?	Mostly: San Bruno and Alcatraz Some: Marin Headlands
10. In what environments were those sandstones deposited originally?	Trenches, submarine canyons
11. Which Franciscan terranes/mélanges contain serpentinite?	Hunters Point and City College
12. How does serpentinite form?	Hydrothermal metamorphism of mantle rock (peridotite) under a seafloor spreading c enter
13. How did the serpentinite get where it is now?	Low density, so migrates up cracks in seafloor and in subduction zone.
14. Which Franciscan terranes/mélanges contain chert and basalt?	Marin Headlands Terrane
15. How did these rocks form?	Mid-ocean ridge volcanism followed by slow, steady accumulation of marine sediments (mostly SiO_2 shells and clay) during plate transit to subduction zone.
16. What is the formation process of a mélange?	Zone between two terranes – one older, the other newly accreting. Lots of shear, locations for serpentinite to migrate, and lots of pieces of both terranes break up and mix up.
17. What is its biggest hazard associated with building or living on mélanges today?	Landslides, because serpentinite and mud matrix are easily washed away or get slippery.
18. At Sutro baths, you observed sandstones and mudstones of the San Bruno Mountain Terrane. What was the original depositional environment of these rocks?	Base of a submarine canyon
19. Up the hill behind Sutro Baths, we reached a level marine terrace. What evidence supported this contention?	Level surface, shells in sediments, sand cover
20. Farther above Sutro Baths, we reached the City College Melange. What were some of the rocks in this mélange?	Chert, greywacke, basalt, serpentinite, metamorphic rocks of many kinds
21. Later we saw a landslide. Why was it there? What contributed to its formation?	Landslide occurred in CC mélange. Waves eroding base of hill contributed.

APPENDIX: Field Trip Preparation List

Arrive to the field trip on time. We'll be moving around.

What to bring Dress in warm clothing that can get wet and dirty. Wear good shoes for hiking up and down hills. Bring a writing utensil and the lab manual. A clipboard or hard surface would be useful. Bring water. (A backpack is recommended to carry water and extra clothing!)

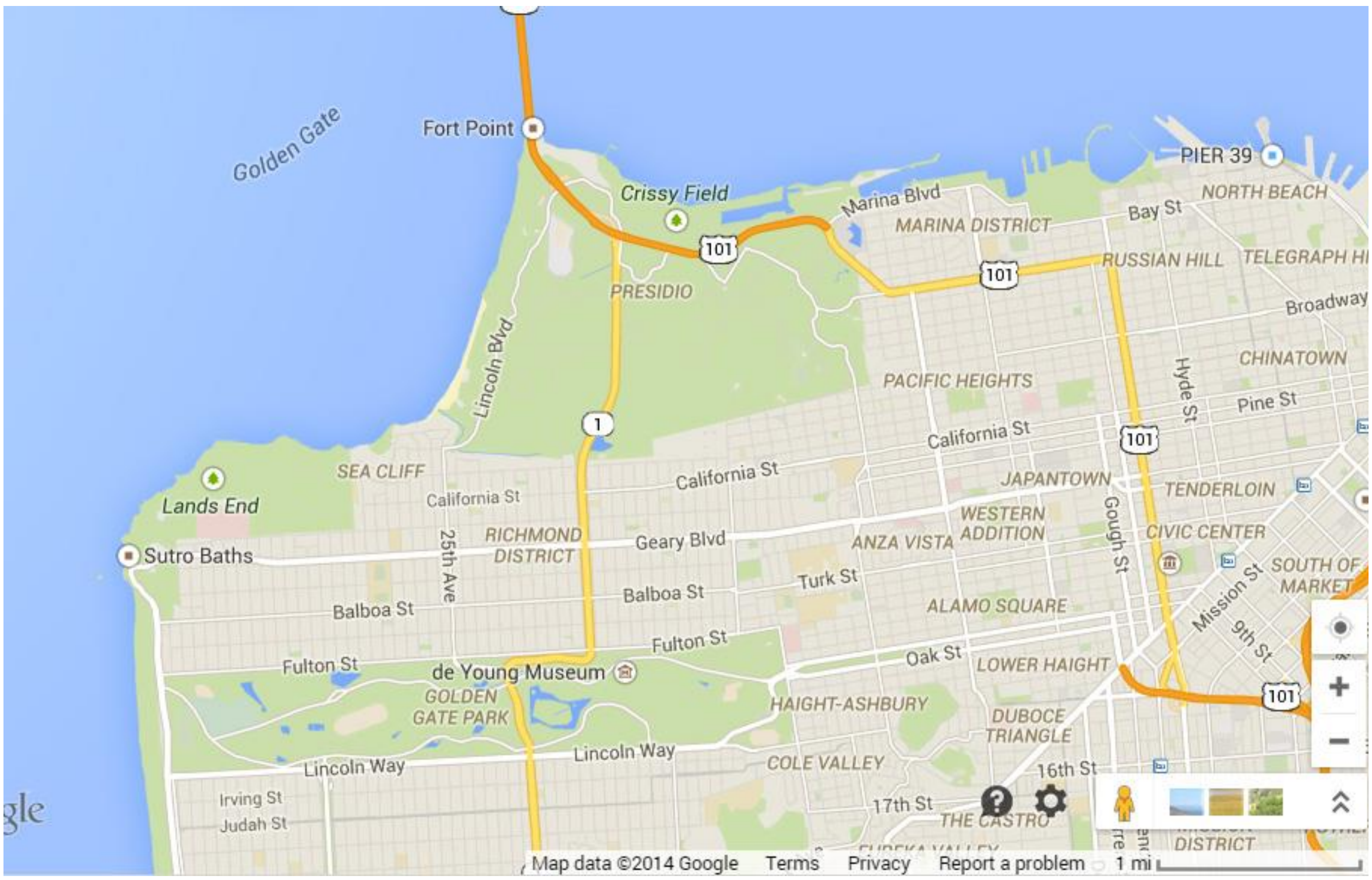
<u>CALIFORNIA GEOLOGY (See Syllabus for MEETING DATE & TIME)</u>

****Note: At our beach stop behind Sutro Baths it is possible you will see more than rocks exposed. On warm, sunny days, you can catch nude sunbathers. Be prepared. No joining in!***

Meeting place: Sutro Baths – bottom of the hill in front of the tunnel in the middle of the ruins (see map).

From CCSF, take Monterey Blvd. west to St. Francis. Go left (west) on St. Francis, which turns into Sloat Blvd. Take Sloat Blvd. all the way to the ocean and take a right, going north on the Great Highway. At the very north end, take your first left after the Cliff House: Merrie Way.

*NOTE: Bus 18 stops right in front of the parking lot.



Google Maps – Northwestern San Francisco. See Sutro Baths and Lands End at center west edge.

Map from National Park Service

APPENDIX: Microscope and Grain Size and % Scales

SCALES FOR MICROSCOPE WORK:

Binocular SWIFT Compound

Objective magnification	Eye piece magnification	Total Magnification	Field of View diameter
4X	10X	40x	5.00 mm
10X	10X	100X	2.00 mm
40X	10X	400X	0.50 mm
100X	10X	1000X	0.20 mm

**DON'T USE THE LARGEST OBJECTIVE*

Binocular SWIFT dissecting

Objective magnification	Eye piece magnification	Total Magnification	Field of View diameter
1X	15X	15x	14 mm
2X	15X	30X	7 mm

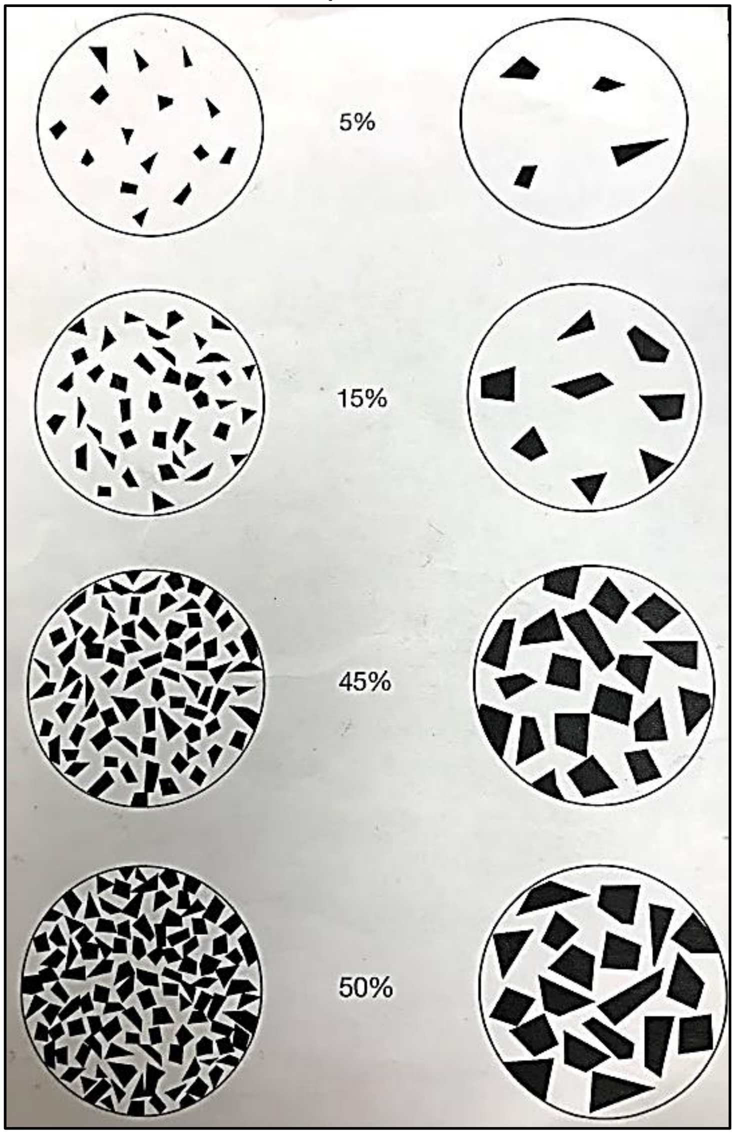
Binocular UNITRIN dissection

Objective magnification	Eye piece magnification	Total Magnification	Field of View diameter
1X	10X	10x	
2X	10X	20X	

Binocular Boreal dissection

Objective magnification	Eye piece magnification	Total Magnification	Field of View diameter
2X	10X	20x	9 mm
4X	10X	40X	5 mm

Grain size and composition % reference chart



Grain size and shape and sorting reference chart