Chapter 12 Geological Structures

Learning Objectives

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

- Describe the types of stresses that exist within the Earth's crust.
- Explain how rocks respond to those stresses by brittle, elastic, or plastic deformation, or by fracturing.
- Summarize how rocks become folded and know the terms used to describe the features of folds.
- Describe the conditions under which rocks fracture.
- Summarize the different types of faults, including normal, reverse, thrust, and strike-slip.
- Measure the strike and dip of a geological feature.
- Plot strike and dip information on a map.

Figure 12.0.1 A fold in sedimentary rocks near Golden and the Kickinghorse River, B.C. The coin in the middle is 26 mm across.

Observing and understanding geological structures helps us to determine the kinds of stresses that have existed within Earth's crust in the past. This type of information is critical to our understanding of plate tectonics, earthquakes, the formation of mountains, metamorphism, and Earth resources. Some of the types of geological structures that are important to study include bedding planes, planes of foliation, dykes and sills, fractures, faults, and folds. Structural geologists make careful observations of the orientations of these structures and the amount and direction of offset along faults.

Media Attributions

- Figure 12.0.1: © Steven Earle. CC BY.

12.1 Stress and Strain

Rocks are subject to **stress**—mostly related to plate tectonics but also to the weight of overlying rocks—and their response to that stress is **strain** (deformation). In regions close to where plates are converging stress is typically compressive—the rocks are being squeezed. Where plates are diverging the stress is extensive—rocks are being pulled apart. At transform plate boundaries, where plates are moving side by side there is sideways or **shear stress**—meaning that there are forces in opposite directions parallel to a plane. Rocks have highly varying strain responses to stress because of their different compositions and physical properties, and because temperature is a big factor and rock temperatures within the crust can vary greatly.

We can describe the stress applied to a rock by breaking it down into three dimensions—all at right angles to one-another (Figure 12.1.1). If the rock is subject only to the pressure of burial, the stresses in all three directions will likely be the same. If it is subject to both burial and tectonic forces, the pressures will be different in different directions.

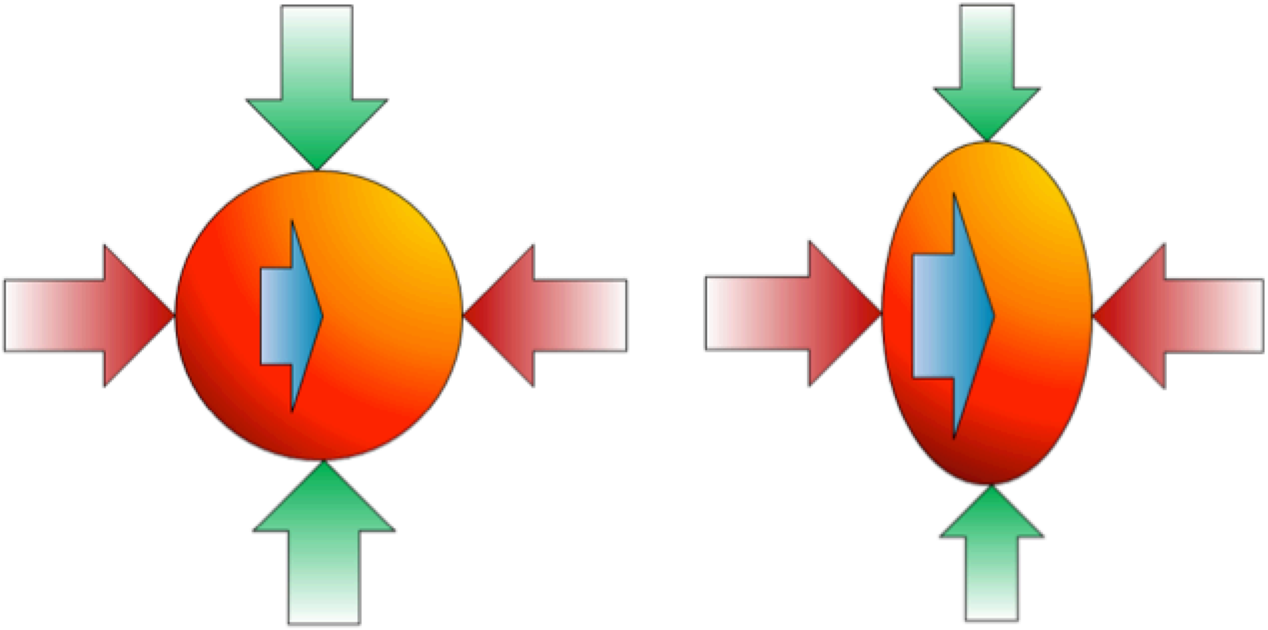

Figure 12.1.1 Depiction of the stress applied to rocks within the crust. The stress can be broken down into three components. Assuming that we're looking down in this case, the green arrows represent north-south stress, the red arrows represent east-west stress, and the blue arrows (the one underneath is not visible) represent up-down stress. On the left, all of the stress components are the same. On the right, the north-south stress is least and the up-down stress is greatest.

Rock can respond to stress in three ways: it can deform elastically, it can deform plastically, and it can break or fracture. Elastic strain is reversible; if the stress is removed, the rock will return to its original shape just like a rubber band that is stretched and released. Plastic strain is not reversible. As already noted, different rocks at different temperatures will behave in different ways to stress. Higher temperatures lead to more plastic behaviour. Some rocks or sediments are also more plastic when they are wet. Another factor is the rate at which the stress is applied. If the stress is applied quickly (for example, because of an extraterrestrial impact or an earthquake), there will be an increased tendency for the rock to fracture. Some different types of strain response are illustrated in Figure 12.1.2.

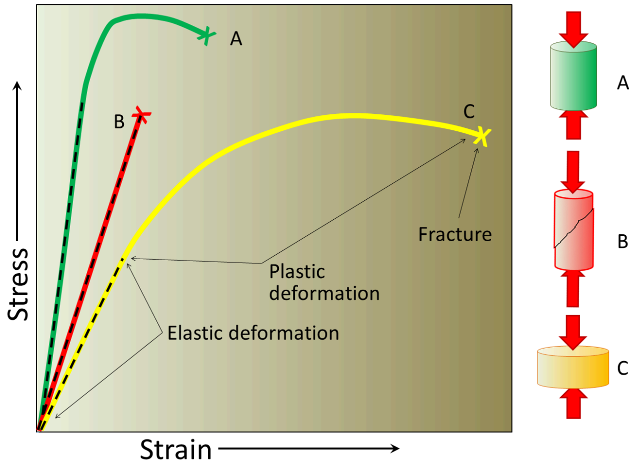

Figure 12.1.2 The varying types of response of geological materials to stress. The straight dashed parts are elastic strain and the curved parts are plastic strain. In each case the X marks where the material fractures. A, the strongest material, deforms relatively little and breaks at a high stress level. B, strong but brittle, shows no plastic deformation and breaks after relatively little elastic deformation. C, the most deformable, breaks only after significant elastic and plastic strain. The three deformation diagrams on the right show A and C before breaking and B after breaking.

The outcomes of placing rock under stress are highly variable, but they include fracturing, tilting and folding, stretching and squeezing, and faulting. A fracture is a simple break that does not involve significant movement of the rock on either side. Fracturing is particularly common in volcanic rock, which shrinks as it cools. The basalt columns in Figure 12.1.3a are a good example of fracture. Beds are sometimes tilted by tectonic forces, as shown in Figure 12.1.3b, or folded as shown in Figure 12.0.1.

a) Fracturing in basalt near to Whistler BC

b) Tilting of sedimentary rock near to Exshaw, AB

a) Stretching of limestone at Quadra Island, BC. The light grey rock is limestone and the dark rock is chert. The body of rock has been stretched parallel to bedding. The chert, which is not elastic, has broken into fragments which are called **boudins**.

d) Faulting within shale beds at McAbee, near to Cache Creek, BC. The fault runs from the lower right to the upper left, and the upper rock body has been pushed up and to the left.

Figure 12.1.3 Rock structures caused by various types of strain within rocks that have been stressed. (A) Fracturing in basalt near to Whistler, BC; (B) Tilting of sedimentary rock near to Exshaw, Alberta; (C) Stretching of limestone at Quadra Island, BC. The light grey rock is limestone and the dark rock is chert. The body of rock has been stretched parallel to bedding. The chert, which is not elastic, has broken into fragments which are called boudins; (D) Faulting within shale beds at McAbee, near to Cache Creek, BC. The fault runs from the lower right to the upper left, and the upper rock body has been pushed up and to the left.

When a body of rock is compressed in one direction it is typically extended (or stretched) in another. This is an important concept because some geological structures only form under compression, while others only form under tension. Most of the rock in Figure 12.1.3c is limestone, which is relatively easily deformed when heated. The dark rock is chert, which remains brittle. As the limestone stretched (parallel to the hammer handle) the brittle chert was forced to break into fragments to accommodate the change in shape of the body of rock. A fault is a rock boundary along which the rocks on either side have been displaced relative to each other (Figure 12.1.3d).

Media Attributions

- Figures 12.1.1, Figure 12.1.2, Figure 12.1.3: © Steven Earle. CC BY.

12.2 Folding

When a body of rock, especially sedimentary rock, is squeezed from the sides by tectonic forces, it is likely to fracture and/or become faulted if it is cold and brittle, or become folded if it is warm enough to behave in a plastic manner.

The nomenclature and geometry of folds are summarized on Figure 12.2.1. An upward fold is called an **anticline** (or, more accurately, an antiform if we don't know if the beds have been overturned or not), while a downward fold is called a **syncline**, (or a synform if we don't if the beds have been overturned). In many areas it's common to find a series of antiforms and synforms (as in Figure 12.5), although some sequences of rocks are folded into a single antiform or synform. A plane drawn through the crest of a fold in a series of beds is called the **axial plane** of the fold. The sloping beds on either side of an axial plane are **limbs**. An antiform or synform is described as **symmetrical** if the angles between each of limb and the axial plane are generally similar, and **asymmetrical** if they are not. If the axial plane is sufficiently tilted that the beds on one side have been tilted past vertical, the fold is known as an **overturned** antiform or synform.

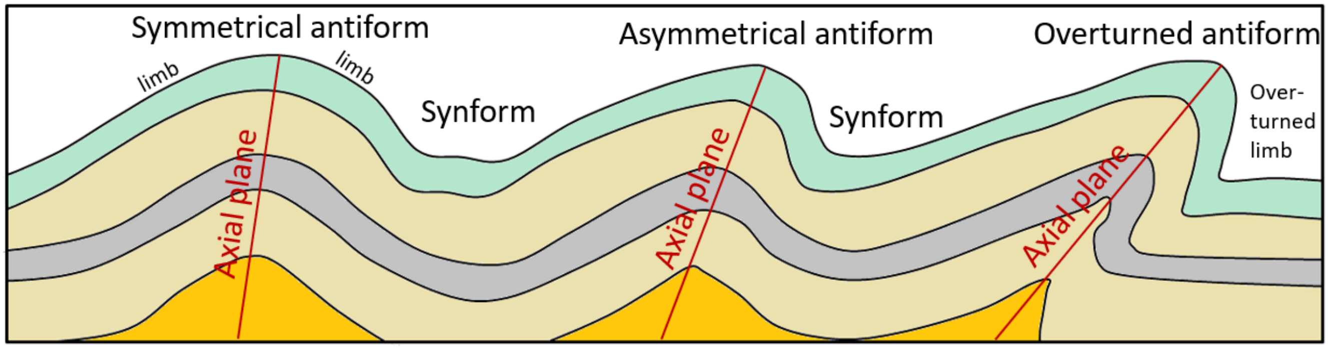

Figure 12.2.1 Examples of different types of folds and fold nomenclature. Axial planes are only shown for the antiforms, but synforms also have axial planes.

A very tight fold, in which the limbs are parallel or nearly parallel to one another is called an **isoclinal fold** (Figure 12.2.2). Isoclinal folds that have been overturned to the extent that their limbs are nearly horizontal are called **recumbent folds**.

Folds can be of any size, and it's very common to have smaller folds within larger folds (Figure 12.2.3). Large folds can have wavelengths of tens of kilometres, and very small ones might be visible only under a microscope.

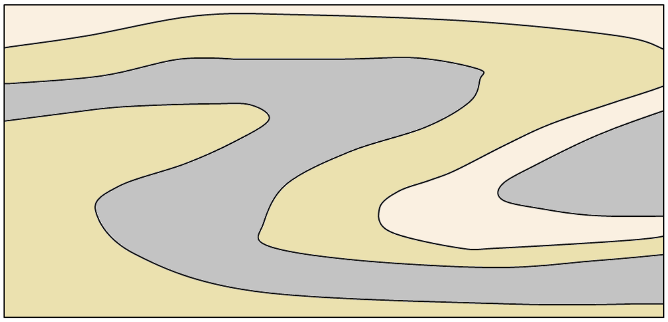

Figure 12.2.2 An isoclinal recumbent fold.

Figure 12.2.3 Folded limestone (grey) and chert (rust-coloured) in Triassic Quatsino Formation rocks on Quadra Island, B.C. The image is about 1 metre across.

Antiforms are not necessarily, or even typically, expressed as ridges in the terrain, nor synforms as valleys. Folded rocks get eroded just like all other rocks and the topography that results is typically controlled mostly by the resistance of different layers to erosion (Figure 12.2.4).

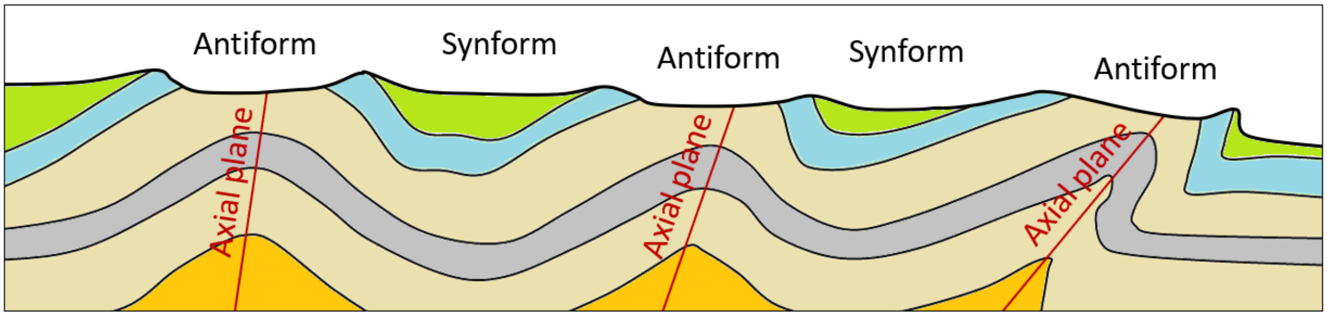

Figure 12.2.4 Example of the topography in an area of folded rocks that has been eroded. In this case the blue and green rocks are most resistant to erosion, and are represented by hills.

Exercise 12.1 Folding style

Figure 12.2.5 shows folding in the same area of the Rocky Mountains as Figure 12.0.1. Describe the types of folds using the appropriate terms from above (symmetrical, asymmetrical, isoclinal, overturned, recumbent etc.). You might find it useful to first sketch in the axial planes.

Figure 12.2.5

See Appendix 3 for Exercise 12.1 answers.

Media Attributions

- Figures 12.2.1, 12.2.2, 12.2.3, 12.2.4, 12.2.5: © Steven Earle. CC BY.

12.3 Fracturing and Faulting

A body of rock that is brittle—either because it is cold or because of its composition, or both— is likely to break rather than fold when subjected to stress, and the result is fracturing or faulting.

Fracturing

Fracturing is common in rocks near the surface, either in volcanic rocks that have shrunk on cooling (Figure 12.1.3a), or in other rocks that have been exposed by erosion and have expanded (Figure 12.3.1).

Figure 12.3.1 Granite in the Coquihalla Creek area, B.C. (left) and sandstone at Nanoose, B.C. (right), both showing fracturing that has resulted from expansion due to removal of overlying rock.

A fracture in a rock is also called a **joint**. There is no side-to-side movement of the rock on either side of a joint. Most joints form where a body of rock is expanding because of reduced pressure, as shown by the two examples in Figure 12.3.1, or where the rock itself is contracting but the body of rock remains the same size (the cooling volcanic rock in Figure 12.1.3a). In all of these cases, the pressure regime is one of *tension* as opposed to *compression*. Joints can also develop where rock is being folded because, while folding typically happens during compression, there may be some parts of the fold that are in tension (Figure 12.3.2).

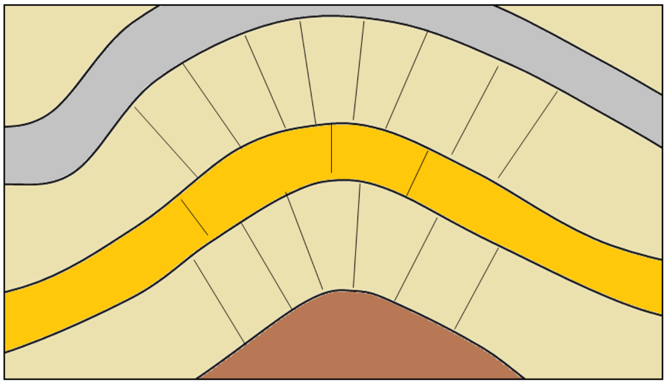

Figure 12.3.2 A depiction of joints developed in the hinge area of folded rocks. Note that in this situation some rock types are more likely to fracture than others.

Finally joints can also develop when rock is under compression as shown on Figure 12.3.3, where there is differential stress on the rock, and joint sets develop at angles to the compression directions.

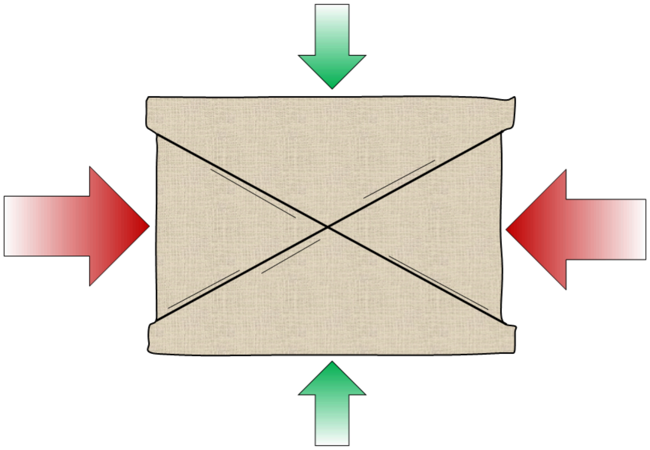

Figure 12.3.3 A depiction of joints developed in a rock that is under stress.

Faulting

A fault is a boundary between two bodies of rock along which there has been relative motion (Figure 12.1.3d). As we discussed in Chapter 11, an earthquake involves the sliding of one body of rock past another. Earthquakes don't necessarily happen on existing faults, but once an earthquake takes place a fault will exist in the rock at that location. Some large faults, like the San Andreas Fault in California or the Tintina Fault, which extends from northern B.C. through central Yukon and into Alaska, show evidence of hundreds of kilometres of motion, while others show less than a millimetre. In order to estimate the amount of motion on a fault, we need to find some geological feature that shows up on both sides and has been offset (Figure 12.3.4).

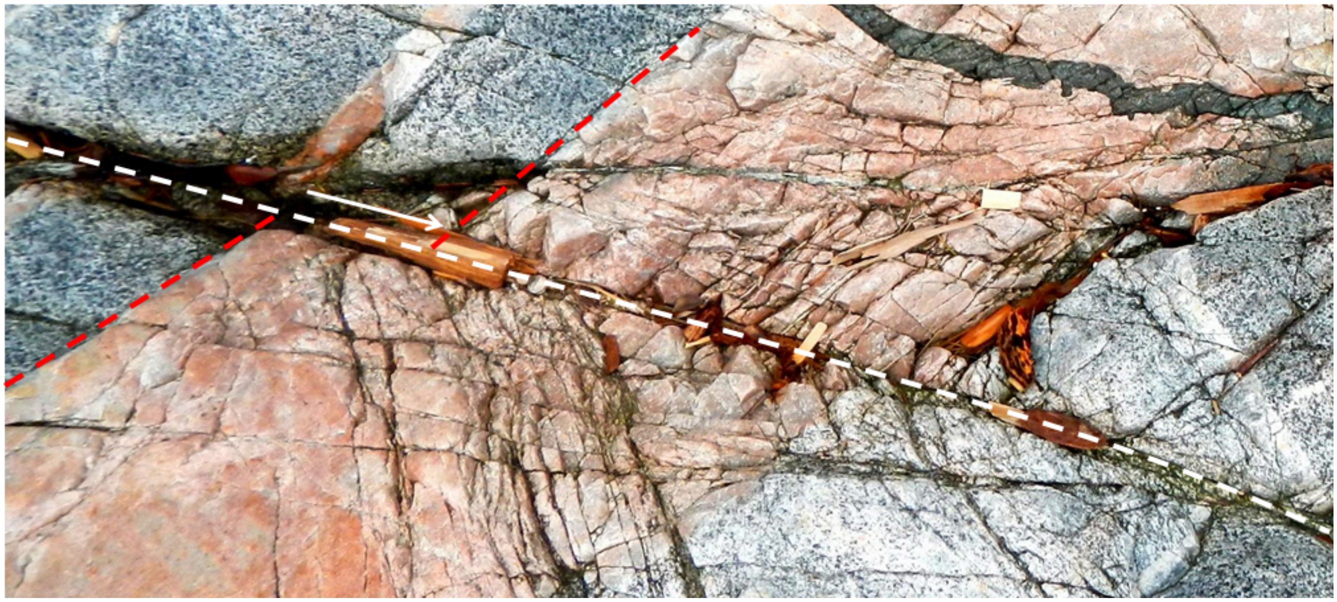

Figure 12.3.4 A fault (white dashed line) in intrusive rocks on Quadra Island, B.C. The pink dyke has been offset by the fault and the extent of the offset is shown by the white arrow (approximately 10 centimetres). Because the far side of the fault has moved to the right, this is a right-lateral fault. If the photo had been taken from the other side, the fault would still appear to have a right-lateral offset.

There are several kinds of faults, as illustrated on Figure 12.3.5, and they develop under different stress conditions. The terms *hanging wall* and *footwall* in the diagrams apply to situations where the fault is not vertical. The body of rock above the fault is called the **hanging wall**, and the body of rock below it is called the **footwall**. If the fault develops in a situation of compression, then it will be a **reverse fault** because the compression causes the hanging wall to be pushed up relative to the footwall. If the fault develops in a situation of extension, then it will be a **normal fault**, because the extension allows the hanging wall to slide down relative to the footwall in response to gravity.

The third situation is where the bodies of rock are sliding sideways with respect to each other, as is the case along a transform fault (see Chapter 10). This is known as a **strike-slip fault** because the displacement is along the "strike" or the length of the fault. On strike-slip faults the motion is typically only horizontal, or with a very small vertical component, and as discussed above the sense of motion can be right lateral (the far side moves to the right), as in Figures 12.12 and 12.13, or it can be left lateral (the far side moves to the left). Transform faults are strike-slip faults.

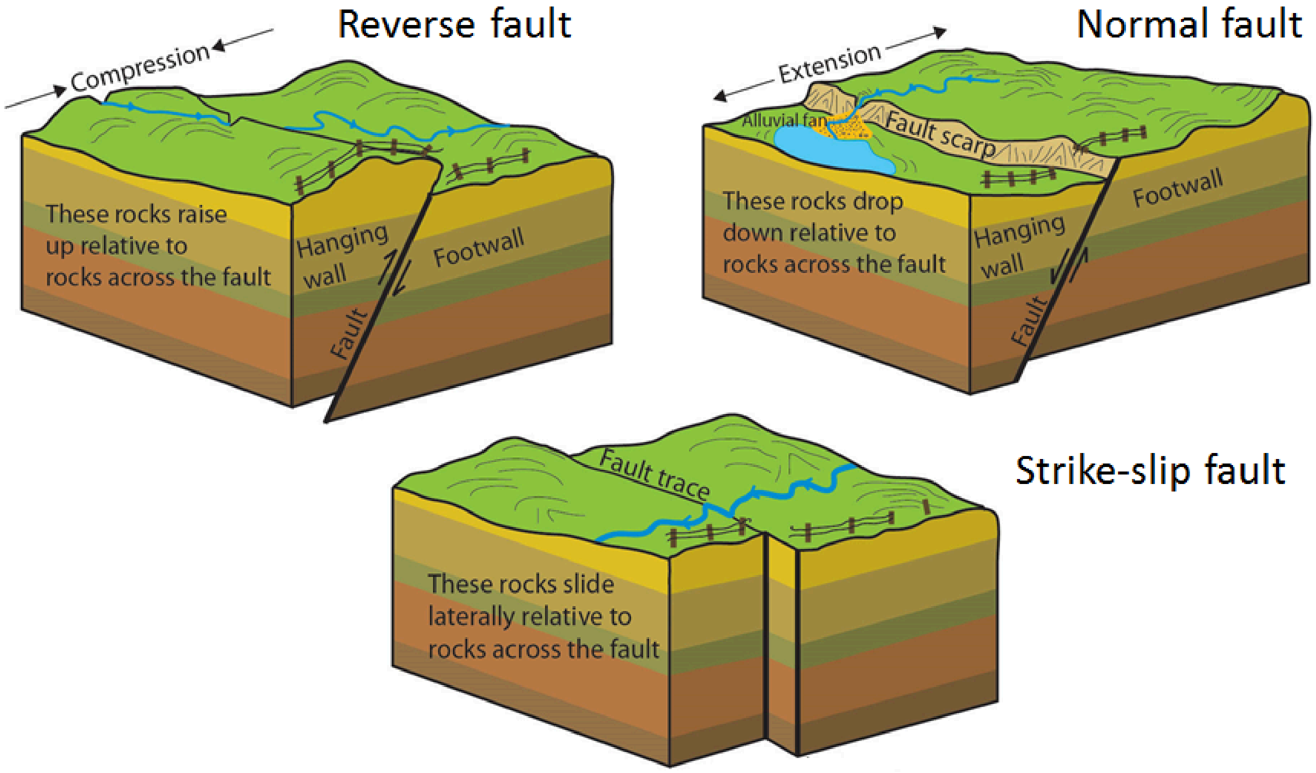

Figure 12.3.5 Depiction of reverse, normal, and strike-slip faults. Reverse faults happen during compression while normal faults happen during extension. Most strike-slip faults are related to transform boundaries.

In areas that are characterized by extensional tectonics, it is not uncommon for a part of the upper crust to subside with respect to neighbouring parts. This is typical along areas of continental rifting, such as the Great Rift Valley of East Africa or in parts of Iceland, but it is also seen elsewhere. In such situations a down-dropped block is known as a **graben** (German for ditch), while an adjacent block that doesn't subside is called a **horst** (German for heap) (Figure 12.3.6). There are many horsts and grabens in the Basin and Range area of the western United States, especially in Nevada. Part of the Fraser Valley region of B.C., in the area around Sumas Prairie is a graben.

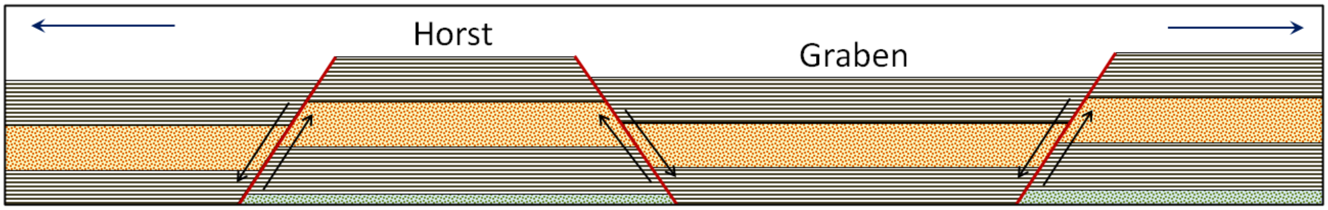

Figure 12.3.6 Depiction of graben and horst structures that form in extensional situations. All of the faults are normal faults.

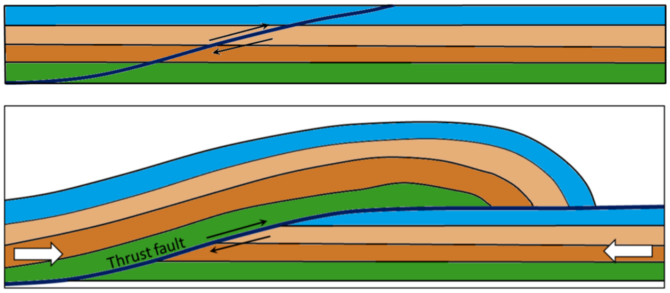

Figure 12.3.7 Depiction a thrust fault. Top: prior to faulting. Bottom: after significant fault offset.

A special type of reverse fault, with a very low-angle fault plane, is known as a **thrust fault**. Thrust faults are relatively common in areas where fold-belt mountains have been created during continent-continent collision. Some represent tens of kilometres of thrusting, where thick sheets of sedimentary rock have been pushed up and over top of other rock (Figure 12.3.7).

There are numerous thrust faults in the Rocky Mountains, and a well-known example is the McConnell Thrust, along which a sequence of sedimentary rocks about 800 metres thick has been pushed for about 40 kilometres from west to east (Figure 12.3.8). The thrusted rocks range in age from Cambrian to Cretaceous, so in the area around Mt. Yamnuska Cambrian-aged rock (around 500 Ma) has been thrust over, and now lies on top of Cretaceous-aged rock (around 75 Ma) (Figure 12.3.9).

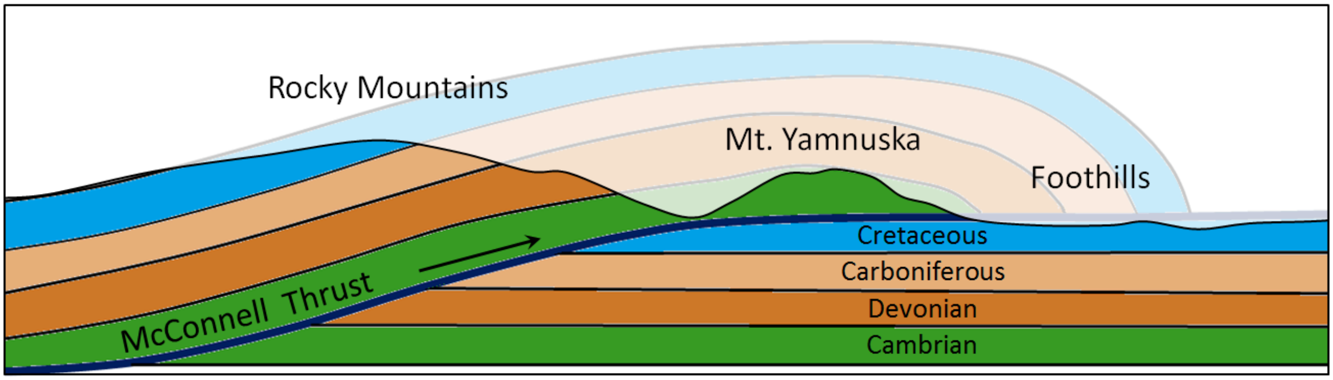

Figure 12.3.8 Depiction of the McConnell Thrust in the eastern part of the Rocky Mountinas. The rock within the faded area has been eroded

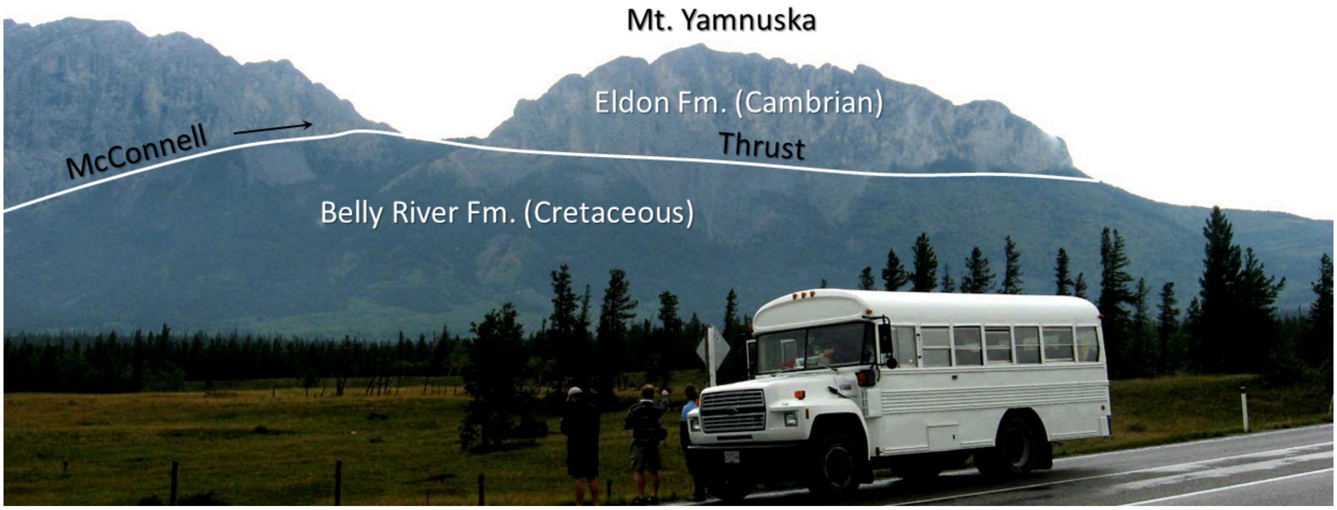

Figure 12.3.9 The McConnell Thrust at Mt. Yamnuska near Exshaw, Alberta. Carbonate rocks (limestone) of Cambrian age have been thrust over top of Cretaceous mudstone.

Exercise 12.2 Types of faults

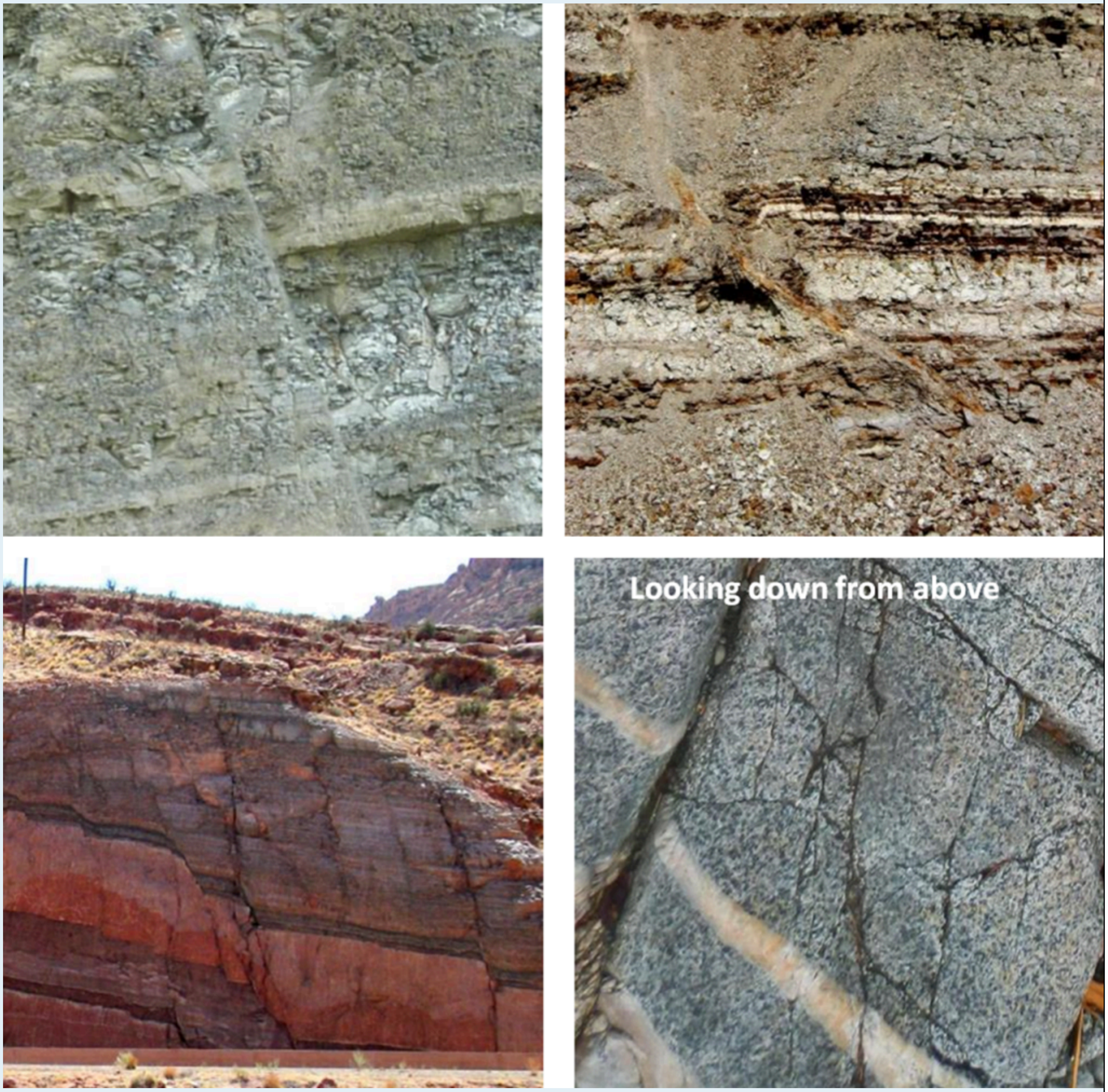

Figure 12.3.10

The four images are faults that formed in different tectonic settings. Identifying the type of fault allows us to determine if the body of rock was under compression or extension at the time of faulting. Complete the table below the images, identifying the types of faults (normal or reversed) and whether each one formed under compression or extension.

Type of Fault and Tectonic Situation
Top left:
Bottom left:
Top right:
Bottom right:

See Appendix 3 for Exercise 12.2 answers.

Media Attributions

- Figure 12.3.1, 12.3.2, 12.3.3, 12.3.4, 12.3.6, 12.3.7, 12.3.8, 12.3.9: © Steven Earle. CC BY.
- Figure 12.3.5: “Fault Types” by the National Park Service. Adapted by Steven Earle. Public domain.
- Figure 12.3.10 (all except bottom left): © Steven Earle. CC BY.
- Figure 12.3.10 (Bottom left): “Moab fault with vehicles for scale” © Andrew Wilson. CC BY-SA.

12.4 Measuring Geological Structures

Geologists take great pains to measure and record geological structures because they are critically important to understanding the geological history of a region. One of the key features to measure is the orientation, or **attitude**, of bedding. We know that sedimentary beds are deposited in horizontal layers, so if the layers are no longer horizontal, then we can infer that they have been affected by tectonic forces and have become either tilted, or folded. We can express the orientation of a bed (or any other planar feature) with two values: first, the compass orientation of a horizontal line on the surface—the **strike**—and second, the angle at which the surface dips below a horizontal plane, (perpendicular to the strike)—the **dip** (Figure 12.4.1).

It may help to imagine a vertical surface, such as a wall in your house. The strike is the compass orientation of the wall and the dip is 90˚ from horizontal. If you could push the wall so it's leaning over, but still attached to the floor, the strike direction would be the same, but the dip angle would be less than 90˚. If you pushed the wall over completely so it was lying on the floor, it would no longer have a strike direction and its dip would be 0˚. When describing the dip it is important to include the direction. In other words. if the strike is 0˚ (i.e., north) and the dip is 30˚, it would be necessary to say "to the west" or "to the east." Similarly if the strike is 45˚ (i.e., northeast) and the dip is 60˚, it would be necessary to say "to the northwest" or "to the southeast."

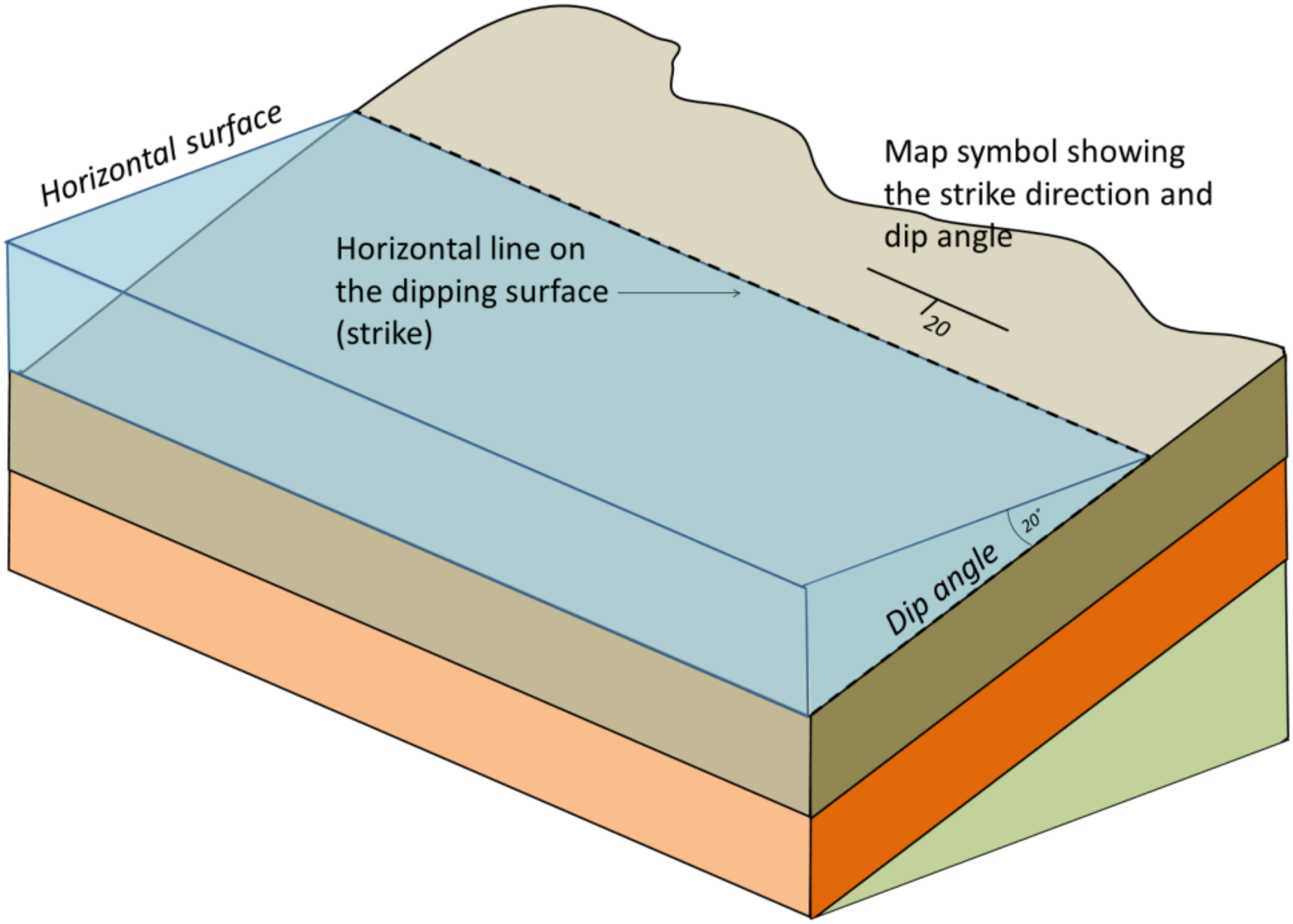

Figure 12.4.1 A depiction of the strike and dip of some tilted sedimentary beds. The dipping beds are shown partially covered with water so that you can visualize a horizontal line on the rock surface. The notation for expressing strike and dip on a map is also shown.

Measurement of geological features is done with a special compass that has a built-in clinometer—a device for measuring vertical angles. An example of how this is done is shown on Figure 12.4.2.

Figure 12.4.2 Measuring the compass direction of the strike (left) and the vertical angle of the dip (right) using a compass with a clinometer.

Strike and dip are also used to describe any other planar features, including joints, faults, dykes, sills, and even the foliation planes in metamorphic rocks. Figure 12.4.3 shows an example of how we would depict the beds that make up an anticline on a map.

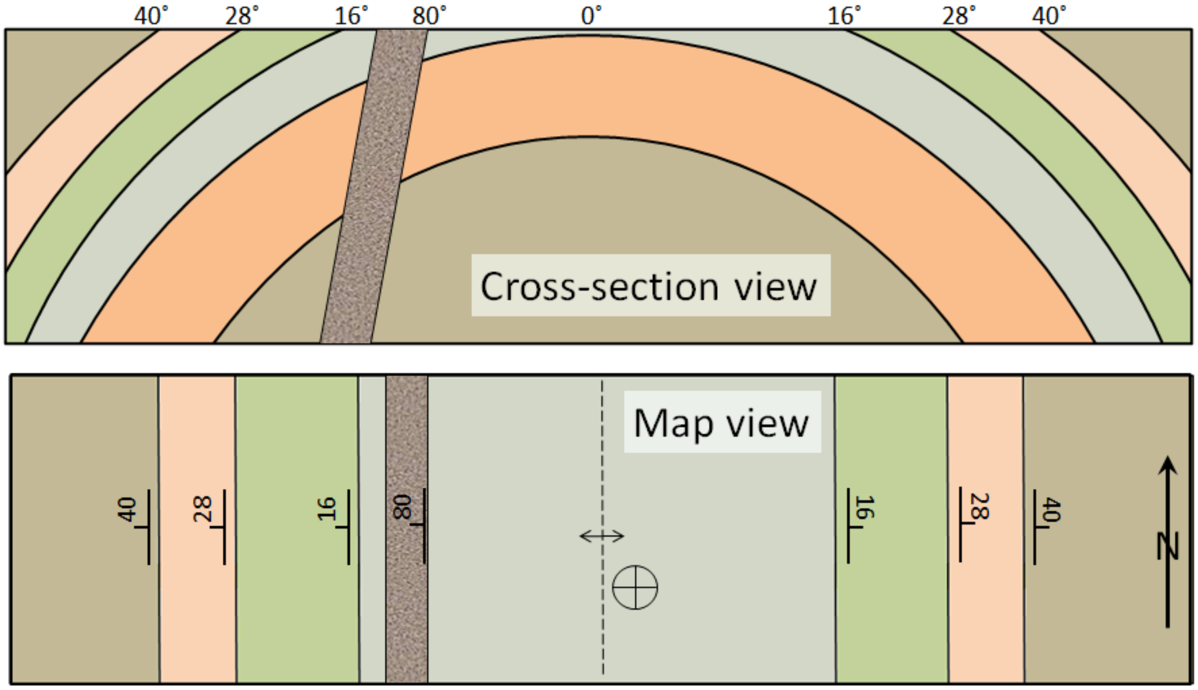

Figure 12.4.3 A depiction of an antiform and a dyke in cross-section (looking from the side) and in map view (a.k.a. plan view) with the appropriate strike-dip and antiform symbols.

The beds on the west (left) side of the map are dipping at various angles to the west. The beds on the east side are dipping to the east. The middle bed (light grey) is horizontal; this is denoted by a cross within a circle. The dyke is dipping at 80° to the west. The hinge of the fold is denoted with a dashed line with two arrows that point away from it. If it was a synform, the arrows would point towards the line.

Exercise 12.3 Putting strike and dip on a map

This cross-section shows seven tilted sedimentary layers (a to g), a fault, and a steeply dipping dyke. Place strike and dip symbols on the map to indicate the orientations of the beds shown, the fault, and the dyke. Then answer the questions.

1. What type of fault is this, and is this an extensional or compressional situation?
2. What are the relative ages of the nine geological features shown here (seven beds, dyke, and fault)? Which are the youngest and oldest?

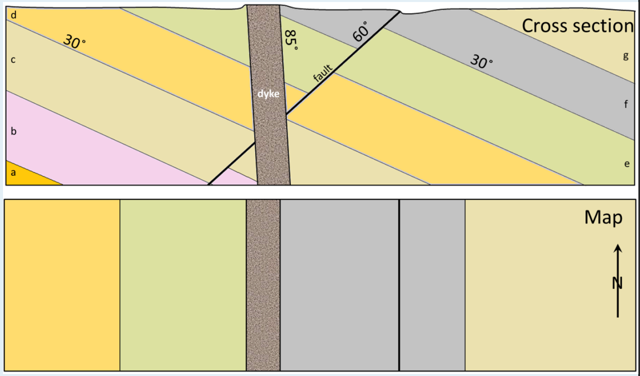

Figure 12.4.4

See Appendix 3 for [Exercise 12.3 answers](#).

Media Attributions

- Figures 12.4.1, 12.4.2, 12.4.3, 12.4.4: © Steven Earle. CC BY.

Summary

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

Section	Summary
12.1 Stress and Strain	Stress within rocks—which includes compression, extension and shearing—typically originates from plate-boundary processes. Rock that is stressed responds with either elastic or plastic strain, and may eventually break. The way a rock responds to stress depends on its composition and structure, the rate at which strain is applied, and also to the temperature of the rock body and the presence of water.
12.2 Folding	Folding is generally a plastic response to compressive stress, although some brittle behaviour can happen during folding. An upward fold is an antiform. A downward fold is a synform. The axis of a fold can be vertical, inclined, or even horizontal. If we know that the folded beds have not been overturned, then we can use the more specific terms: anticline and syncline.
12.3 Fracturing and Faulting	Fractures (joints) typically form during extension, but can also form during compression. Faulting, which involves the displacement of rock, can take place during compression or extension, as well as during shearing at transform boundaries. Thrust faulting is a special form of reverse faulting.
12.4 Measuring Geological Structures	It is important to be able to measure the strike and dip of planar surfaces, such as a bedding planes, fractures or faults. Special symbols are used to show the orientation of structural features on geological maps.

Questions for Reviews

1. What types of plate boundaries are most likely to contribute to the following?: a) compression, b) extension, and c) shearing.
2. Explain the difference between elastic strain and plastic strain.
3. List some of the factors that influence whether a rock will deform (in either an elastic or plastic manner) or break when placed under stress.
4. Label the types of folds in this diagram, and label any of the important features of the folds.

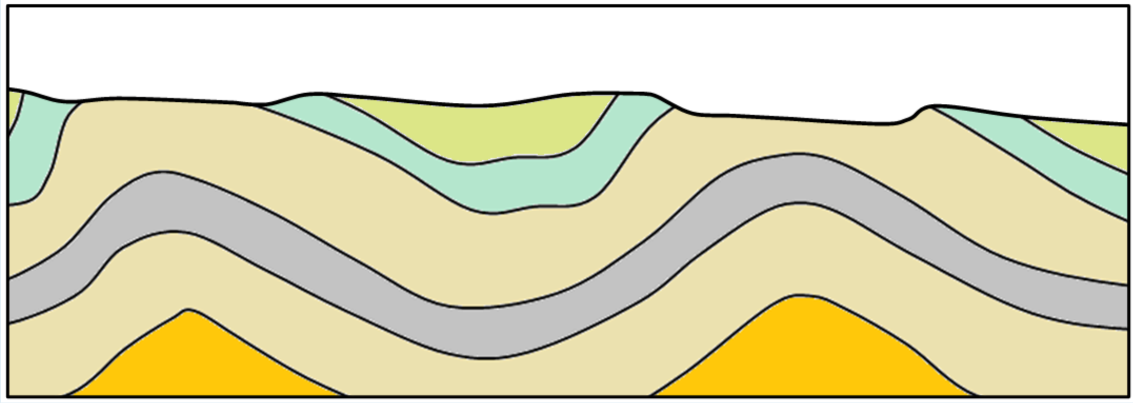

Figure A

5. Explain why fractures are common in volcanic rocks.
6. What is the difference between a normal fault and a reverse fault, and under what circumstances would you expect these to form?
7. What type of fault would you expect to see near to a transform plate boundary?
8. This diagram is a plan view (map) of the geology of a region. The coloured areas represent sedimentary beds.

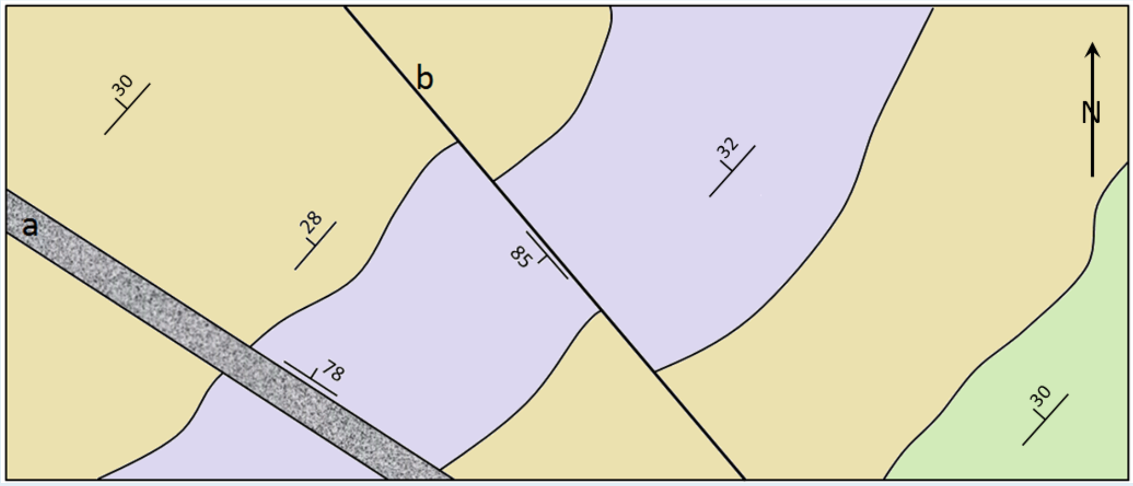

Figure B

i) Describe in words the *general* attitude (strike and dip) of these beds.

ii) Which of these beds is the oldest?

iii) What is “a” and what is its attitude?

iv) What is “b” and what is its attitude?

v) Which of these terms applies to “b”: “left lateral” or “right lateral”?

Answers to Review Questions can be found in Appendix 2.

Media Attributions

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