LESSON 6: GEOLOGIC STRUCTURE AND THE PARASHANT LANDSCAPE

GEOLOGICAL ADVENTURES AT PARASHANT

EXPLORING THE GEOLOGY OF

GRAND CANYON-PARASHANT NATIONAL MONUMENT

LESSON 6 GUIDE: GEOLOGIC STRUCTURE AND THE PARASHANT LANDSCAPE

OVERVIEW

In this activity, students use modeling clay to simulate and study three kinds of stress that create geologic structures: tensional, compressional, and shear. In Part B of the activity, they apply what they have learned about stress to model the formation of faults, folds, and uplift using their modeling clay. Each group is assigned a different type of structural feature to model. They use instructions to produce a structure using modeling clay, but must use what they have learned to explain the forces that led to the feature. Each group then presents the structural model to the rest of the class. Students read about the processes of uplift, folding, and faulting in the context of plate tectonic theory and the formation of Parashant's landscape features.

Objectives After exploring stresses, folding, and faulting of rocks with modeling clay, reading about the forces that cause folding and faulting at Parashant, and interpreting a cross-section of faulted rocks on the monument, students will understand:

- Three basic types of stress that rocks are subjected to.
- Brittle and ductile deformation
- Folds, faults, and joints are ways that rocks respond to stress
- Common types of folds and faults and the types of stress that produce each
- Large-scale geologic forces have played an important role in shaping the Parashant landscape.

Concepts Stress, strain, ductile versus brittle deformation, jointing, normal, reverse, and strike-slip fault, anticline, syncline, monocline.

Duration Three 45-minute class periods

Audience Students in grades 6 to 9

Materials **Part A: Modeling Stress and Strain**

- clay model of rock layers from prior lesson
- four pieces of colored modeling clay (left over from earlier lessons)
- Styrofoam plate or wax paper
- plastic bottle cap
- metric ruler
- piece of dental floss

Part B: Modeling Folds and Faults

- clay model of rock layers (from prior lessons)
- several pieces of colored modeling clay (left over from prior lessons)
- Styrofoam plate or wax paper
- metric ruler
- dental floss
- small thin wood block or thin textbook (group B only)

- dropper bottle of liquid soap (groups D, E, and F)

Extensions **For honors, gifted, or higher grade-level students**

- Work in the concepts of strike and dip into Part B of **Explore**. This would be useful for students who are expected to work with or interpret geologic maps.
- See Part A, Step 5 of the Explore phase of this teacher guide for ideas about integrating mathematics (ratios and percents) and graphing into the study of stress and deformation.

Resources

- An overview of structural geology written by Dr. James Harwood of Blackhawk State College is available at facweb.bhc.edu/academics/science/harwoodr/Geol101/study/structur.htm
- Most of Parashant has been mapped by George Billingsley (and colleagues) at the USGS Flagstaff. The maps contain reports and overview pamphlets. Some maps include photos and cross-sections. The maps and pamphlets are available as pdf downloads at http://geopubs.wr.usgs.gov/docs/geologic/az/arizona.html.

ENGAGE **10 minutes**

The photo shows folded and faulted sedimentary rocks of the Triassic Moenkopi Formation in a small basin at Parashant known as “Hell’s Hole”. The Hurricane Fault which produced the Hurricane Cliffs that run north-south through northern Arizona runs through this basin. According to a recent geologic map made by the USGS, the Hurricane Fault has a vertical displacement of 610 meters nearby. This is very likely the reason behind the folding and faulting of layers shown in the photo. Responses to the questions (students will probably not provide all this detail – it is more for your knowledge):

1. The rock layers are not lying flat (the photo was taken from above the outcrop rather than ground level, but it should be clear that the layers have been “disturbed.” The layers are tilted – you can see the end of the layers pointing upward.
2. The layers are not continuous. You cannot trace a single layer all the way across the outcrop. Some of this is due to layers being obscured by erosion on slopes, but faulting also controls the lack of continuity.
3. An appropriate response would be that somehow the rocks got squeezed, compressed, tilted, or lifted up in some way by forces inside the Earth.

Ask volunteers to share ideas. Accept all reasonable ideas and write them on the board or on an overhead transparency. Avoid providing the “right” answer – students will learn the names of fold, faults, and stresses on rocks in the explore phase of the lesson.

EXPLORE 60 minutes

Part A: Modeling Stress and Strain 30 minutes

In Part A of the Exploration phase, students use clay to model forces that deform rock layers. This part of the lesson gives concrete experience with **stress** (the force applied to rocks) and **strain** (how rocks deform in respond to stress). There are two major types of deformation – **elastic** (objects return to their original shape after stress is removed, like a rubber band or bending a twig) and **plastic** (objects do not return to their original shape after stress is removed, like snapping a twig. Elastic deformation precedes plastic deformation. Students model plastic deformation in the two parts of the Explore phase.

Try the activity yourself before you teach it so that you can identify potential sticking points for your students. Photographs in this teacher's guide will help you to see how models are set up, but the exact results obtained will vary depending upon thickness of layers, amount of stress applied, and so on.

FIGURE1. Materials used in Explore, Part A. The balls of clay are rounded scraps from earlier lessons. Dental floss used in the lesson is not shown.

Materials students will need are shown in Figure 1. Saving scraps of clay when students trimmed clay models in earlier lessons and combining pieces of the same color allows you to use one 12-ounce box of modeling clay per group for lessons 2-6. You need a small water bottle cap for marking circles in the clay. A pencil point or toothpick can be used to draw cross-lines (see below).

You could reduce the time devoted to this activity in half (20 minutes) by eliminating measuring (see step 4 below) and assigning groups to one of the three types of stress (10 minutes), then having them present their results to the class (10 minutes).

1. Gathering materials as "kits" for each group ahead of time will save time.
2. You might model how to roll and shape the clay. It is quite easy once you get the hang of it, but younger students may struggle a bit. Squash the cylinder of clay down to make a rough rectangle, hold it against a metric ruler on the table, working the clay to get the length and widths about right, then slap the clay on the table to flatten the two large surfaces and tap the ends of the clay down on the table to flatten and square off the four smaller ends. Students need not worry about getting the dimensions exactly right, but you can help them appreciate

experimental control by discussing why it is better to do the three stress tests with shapes of similar size.

3. Students need only make light marks in the clay so that the circle formed by the bottle cap and the cross-lines are visible. The cross lines should be at about right angles (perpendicular), as shown in Figure 2.

4. If you want to trim some time from this activity, tell students that they should make rough sketches rather than measure the lengths of the lines. Measuring the lines increases the likelihood that they will draw diagrams that closely represent the actual deformation, but since they will not be doing quantitative analysis (e.g., calculating the ratio between the lengths of the axes for each deformation), a simple sketch without measuring lengths will save time.

FIGURE2 Side view of clay model with circle (made with bottle cap) and two perpendicular cross lines.

If you wish to make the lesson even more quantitative, have students label the two axes H for horizontal and V for vertical, calculate the ratio of H to V. For the original shape, the ratio of H to V is 1:1. They can calculate how the ratio changes as a factor of percentage deformation (compression or extension). The percentage deformation would be computed as follows; (new length of the clay [not the circle] divided by the original length of the clay) times 100. Students could then graph the percentage deformation on the X axis versus the ratio of horizontal to vertical ratios on the Y axis to answer a research question like: “What is the relationship between the amount of stress and the amount of deformation of a clay model?” This should work for tensional and compressional stress, but shear stress might be too difficult to measure and quantify with modeling clay.

5. Students can compress the model by holding the model in their hands and pressing inward or by leaving the model on the table and pressing inward. Apply the stress equally and directly to avoid any shearing. Stop when the model is about 50% compressed.

FIGURE 3 Side view of clay model after compressional stress was applied. Note that the clay is about half the original length, and that the circle is deformed, while the cross lines remain perpendicular.

6. Figure 3. shows the results of compressing the clay to about 50% of its original length. Note that the clay is wider top to bottom,

shorter side to side, and that even the width of the horizontal cross line increased (it looks wider). A drawing of the compressed model is shown in Figure 6.

7. Students should try to reshape the model to about the same dimensions as the first stress test. Reworking the clay with your hands a few times before reshaping will eliminate traces of the original cross lines and circle. After they make the rectangular shape, they need to remember to do the circle and cross lines.

8. The challenge of modeling tensional stress is to avoid tearing the clay apart. The best way to do this is to hold the model with the thumb and four fingers of each hand (rather than just thumb and one finger) and pull slowly. It is okay to stop and start a few times. Try this yourself to identify tips to give your students.

9. See Figure 4 for the results of a tensional stress applied to clay. The model was stretched to almost 20 cm long without tearing. Figure 6 shows a drawing of the same model shown in Figure 4. Note that cross lines are perpendicular on the model and the drawing. Drawings will reveal how carefully students are observing and measuring the model. Remind students to focus on the shape of the circle, not the whole clay.

FIGURE 4 Side view of clay model after tensional stress was applied. Note that the clay is about twice its original length, and that the circle is deformed. The cross lines remain perpendicular.

10. Students reshape the model for the third and final time in this activity. Again, they should strive to get close to the original dimensions and remember to make the circle and cross lines.

11. When students model shear stress, they focus on a top view because it is easier to model shear stress when the model is lying flat on the table. The

FIGURE 5 Top view of a clay model after shear stress was applied. Note that the circle is highly deformed. The cross lines are no longer perpendicular, but at a lower angle to one another.

top view reveals the strain on the clay.

12. After you have tried the shear stress yourself, decide whether you want to demonstrate this to students. At the very least, you could demonstrate the motion using your hands – pull one hand towards you and move the other away. Shear is like tearing – two forces moving in opposite directions past each other (you might ask if students knew that scissors are also called “shears”).

13. Figure 5 shows the results of a shear stress, and Figure 6 shows the drawing of the model shown in Figure 5. The amount and shape of the circle used to show strain will vary depending upon how students stress the clay model (there is no single “right” answer).

14. Students’ responses should have elements of the descriptions provided below. You might wish to type this up and leave spaces for them to fill in key words that are underlined below.

When the clay model is subjected to compressional stress, the model gets shorter parallel to the direction of stress and wider perpendicular to the stress. The cross lines remain perpendicular to one another.

When the clay model is subjected to tensional stress, the model gets longer parallel to the direction of stress, and shorter perpendicular to the direction of stress. The cross lines remain perpendicular to one another.

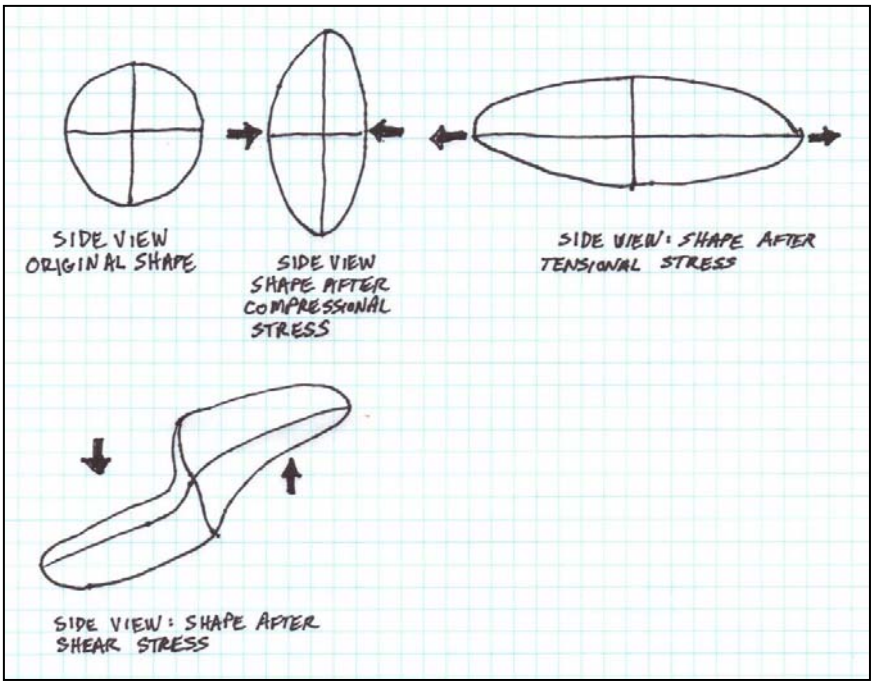


FIGURE 6. Drawings showing the results of stresses applied to the models tested for this guide. Sketches are drawn to scale to each other.

When the clay model is subjected to shear stress, the model is bent and stretched and longer at a 45 degree angle to the directions of stress.

15. Students should wash their hands with antibacterial soap after handing modeling clay.

Part B: Modeling Folds and Faults 45 minutes

In this part of the activity, students model geologic structures that results from two different types of plastic deformation: ductile (when rocks bend or **fold** without breaking) and brittle (when rocks break by **faulting** or jointing). Although students will explore the processes separately, folding and faulting are commonly closely associated in nature. For example, monoclines (one-sided folds) on the Colorado Plateau form where sedimentary rocks are draped over deeper basement faults.

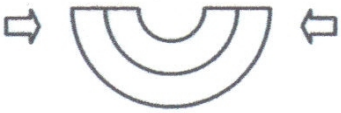
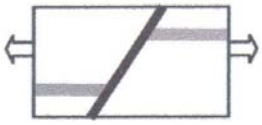
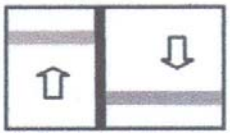
FIGURE 7. Materials used in Part B. Not shown is a wood block (or thin book) used to make the monocline.

Assign each group one type of strain to model. Have them fill in the correct row in Table 1 for their model. Then, have each group demonstrate its model to the class. As presentations are made and ideas and models are discussed, students complete the remainder of Table 1. Use Table 1 as a guide to assign groups to one of the six types of deformations. It helps to think of folds as having a wave-like structure – anticlines are like crests and synclines are like troughs.

Most of the **materials** each group will need for the activity are shown in Figure 7. Clay is simply recycled from the earlier activity. Group B (monocline) will need a thin textbook or wood block. Groups D, E, and F will need to apply a drop or two of liquid soap onto the fault plane of their models to lubricate the surface because clay is sticky and the sides of the fault will not slide past one another without lubrication.

A completed copy of Table 1 is shown on the following page. Photos of what the models should look like and how to arrange materials follow the table. This exercise requires a bit of critical thinking, and students may struggle with some aspects of the cells. Be flexible and encourage discussion, critical thinking, and risk-taking, but be prepared to adjust expectations based upon the needs and abilities of your students.

Table 1. Results of Modeling Stress and Deformation of Rocks

Structure	Stress Compressional, Tensional, or Shear	Deformation Brittle or Ductile	Diagram Label Top or Side View; Use arrows to show directions of stress	Explanation
A. Anticline	Compressional	Ductile	Side View	Forces compress rock making it bend.
B. Syncline	Compressional	Ductile	Side View 	Forces compress rock making it bend.
C. Monocline	Tensional/Shear	Ductile	Side View	Forces push upward on one end of rock layers, bending them into a fold with one side.
D. Normal Fault	Tensional	Brittle	Side View 	Forces pull rocks apart, causing them to break. Rocks above the break slide down the break.
E. Reverse Fault	Compressional	Brittle	Side View	Forces push rocks together until they break. Rocks above the break are pushed up the break.
F. Strike-Slip Fault	Shear	Brittle	Top View 	Rocks are broken by forces that push them past each other horizontally.

A. Anticline

Anticlines are most commonly caused by compressive stress. Compression can arise in a number of ways. Geologists recognize anticlines in the field by 1) seeing strata that dip away from the axis of the fold; 2) noting that erosion eposes progressively older sediments as you move towards the fold axis (students would see the latter relationship if they sliced the clay model horizontally). Cylindrical anticlines (perfectly shaped like the top half of a cylinder lying on its side on a table) are rare in nature. Most anticlines (and synclines) “plunge” into the Earth at and angle.

Students will model the compression by pressing the ends of the clay together. However, the “trick” is to create the fold, not simply repeat the compression stress test from Part A. Therefore, it helps if they use their fingers to push up a little from the bottom to get the fold started. They need to ignore this push when interpreting the model and describing the stresses. Figure 8 shows construction of a sample model.

FIGURE 8. Making an anticline. Upper left: Large piece of clay cut into 3 pieces by floss. Upper right: Five pieces flattened into rectangular shapes. Lower left: Stacked layers. Lower right: Anticline fold.

B. Syncline

Synclines are like basins – they are U-shaped folds in which strata dip towards the fold axis and the strata become younger as one moves towards the fold axis.

To make a syncline, students use the same procedure for making an anticline, except that they push the center of the clay downward to make a U-shaped fold.

C. Monocline

A monocline is an open, step-like structure in which the layers are all inclined in the same direction on either side of the fold axis. On the Colorado Plateau, there are broad areas of nearly flat lying strata (plateaus) separated by bends along monoclinal folds. Imagine a normal fault in the basement rocks with sedimentary rocks draped over the top. This is one of many ways that monoclines form, and probably the simplest way for students to model. In this case, the vertical edge of the book (see Figure 9 below) would equate to the fault plane of a normal fault, the book as the upthrown block of the normal fault, and the table as the down-dropped side of the normal fault.

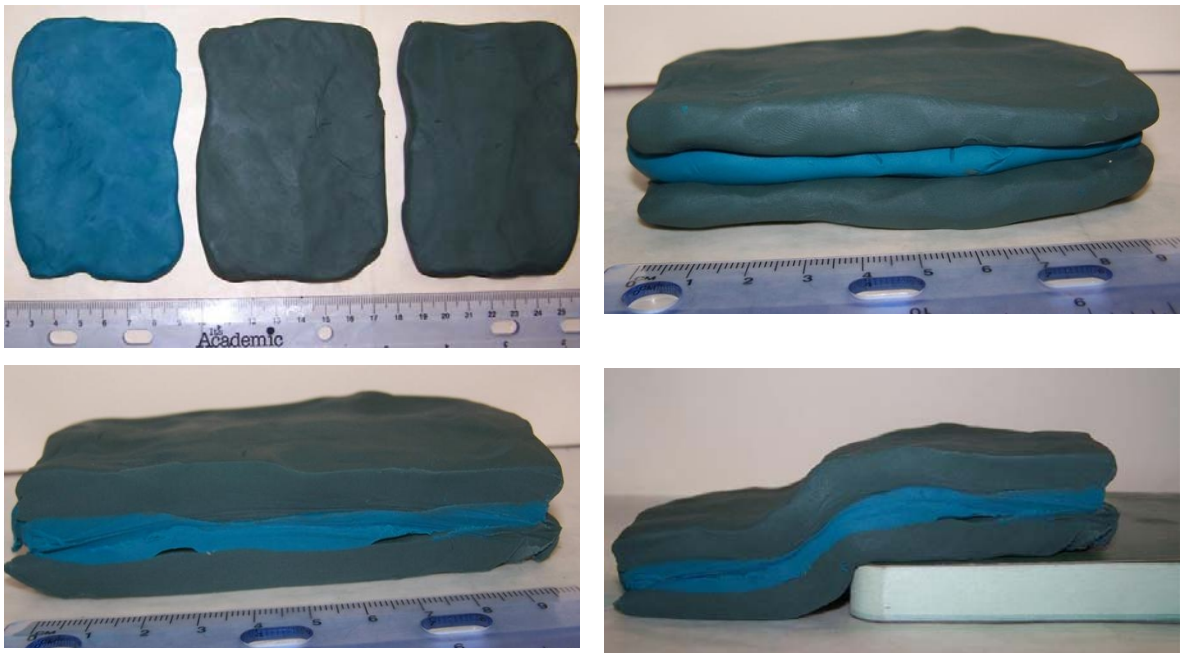


FIGURE 9. Upper left: Three flat pieces of clay needed for structure. Upper right: Layers stacked with alternating colors. Lower left: Thin slice taken off side of long face to reveal layers more clearly. Lower right. Finished monocline fold.

D. Normal Fault

Normal faults most often form due to tensional stress. Uplifting a broad region like the Colorado Plateau stretched the brittle crust, creating tension which fractured the strata. A number of north-south trending normal faults dissect the Colorado Plateau. At Parashant, the huge, nearly vertical fault scarps that make up the Hurricane Cliffs and Grand Wash Cliffs are dramatic examples of this structural feature.

Figure 10 shows a side view through a normal fault created in a clay model (with stress directions shown in arrows, and motions of the fault blocks shown for your information). A drop or two of liquid soap will lubricate the surface so that the

sides can slide along the fault. The relatively high angle of the normal fault may lead students to have difficulty comprehending how normal faults are due to tensional stress. If this happens, ask them to put their left hand over their right hand in front of themselves, palms down, with elbows out and fingers parallel to their bodies (fingers point towards opposite elbow). The surface between their hands would be the fault plane. Then ask them to move their elbows apart to slide their left hand (the hanging wall of the fault because it hangs over the fault plane) down over their right hand (the footwall or layers below the fault plane). Challenge them to obtain this relative motion by pushing their hands together rather than pulling. It isn't possible to create this relative motion through compression.

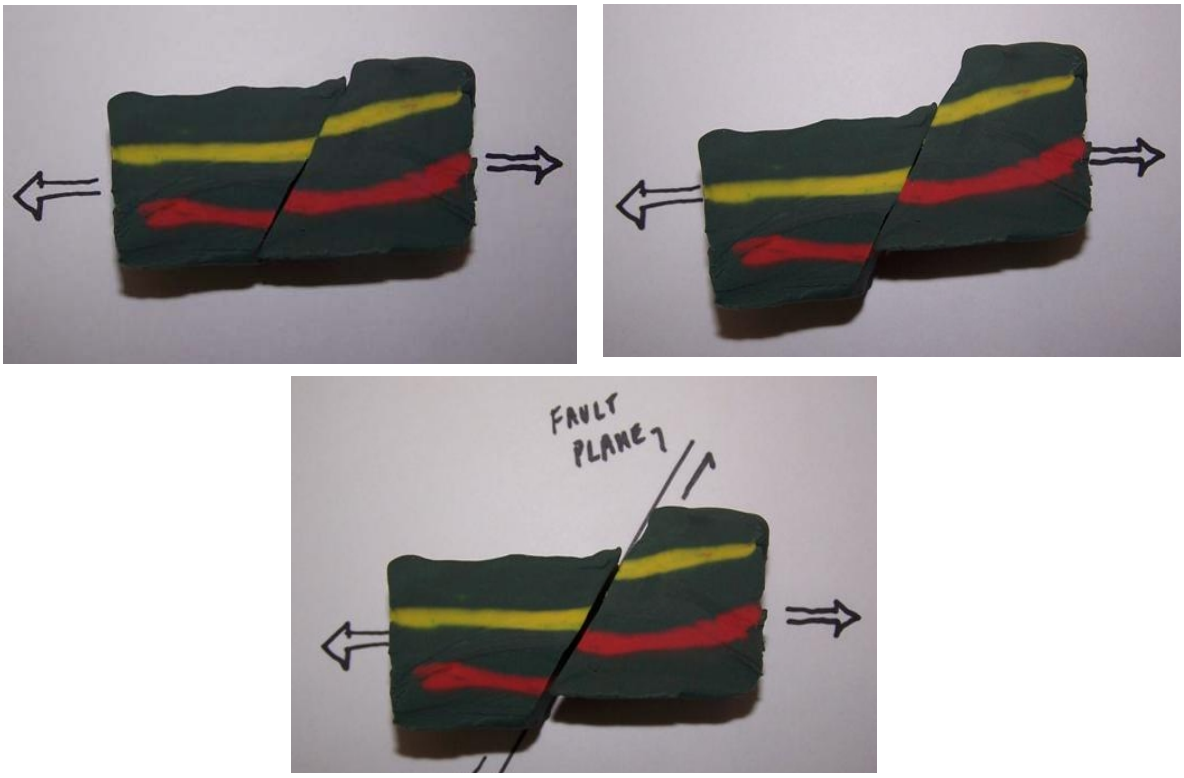


FIGURE 10. Upper left: Side view of the start of normal fault movement. Upper right: Side view of the completion of normal fault movement. Lower: Normal fault showing fault plane, stresses, and direction of movement along the fault. On all photos, footwall is to the right, and hanging wall to the left of fault.

E. Reverse Fault

Reverse faults form most often due to compression – forces that push rock together, breaking the rock and creating a fault. Low-angle (< 30 degree) reverse faults are called thrust faults. If you wish to form eight groups, you can add this model to the list as model G.

Figure 11 shows the reverse fault model. In nature, rock layers do not hang over the top of one another like this. They are smoothed by erosion. The angle of inclination of the fault and the age of the rock layers on either side provide some of the evidence used to identify them. Note for example that if the hanging wall on the model below was eroded, the “older” yellow layer on the left (hanging wall) side of the fault would be at the same position as the top green “younger” layer on the footwall side.

FIGURE 11. Side view of reverse fault with arrows showing direction of movement of rock units along the fault plane, and larger arrows showing the direction of compressional stress.

Lubricating the surfaces of the fault with a drop of liquid soap on each side is necessary to get the sides to slide past one another.

F. Strike-slip Fault

Strike-slip faults arise due to shear stress – forces moving past one another. Strike-slip faults are typically nearly vertical and move rock horizontally past each other on either side of the fault. The San Andreas Fault in California is a famous example. When the side across the fault moves to the right, it is called a right-lateral strike-slip fault. If the side across the fault moves to the left, it is a left-lateral strike-slip fault. The fault shown in Figure 12 is right lateral. The line traced on the model helps to illustrate the relative motion, and would represent the motion of rock, a fence-line, or stream course in nature. Horizontal motion dominates over vertical motion on strike-slip faults.

FIGURE 12.. Strike-slip faulting. Upper left: Top view prior to faulting. Upper right: Side view prior to faulting. Lower left: Top view after faulting showing motion along fault plane. Lower right: Side view after faulting.

EXPLAIN

Assign for reading during class or as homework (even if the entire activity has not yet been completed). You can supplement the explanation phase of the lesson with a discussion or lecture. Photographs of local or regional structural features would illustrate products of tectonic stress and provide relevant examples to students.

ELABORATE **40 Minutes**

In this activity, students interpret a cross-section of the western side of Parashant. The western edge marks the transition zone between the Colorado Plateau to the east and the Basin and Range to the west. Thus, the cross section illustrates one of the more prominent faults and cliffs of the monument (Grand Wash Cliff) and there are more faults here for students to interpret. The intended focus is geologic structure, not other geological principles (uncomformities, geologic time, geologic history, etc.), which students do not need to know in order to interpret the cross-section.

Students will need a clean copy of the cross section and legend, and a ruler (preferably transparent).

Have students work in groups to promote discussion. Things you might wish to point out to students to introduce them to the activity include:

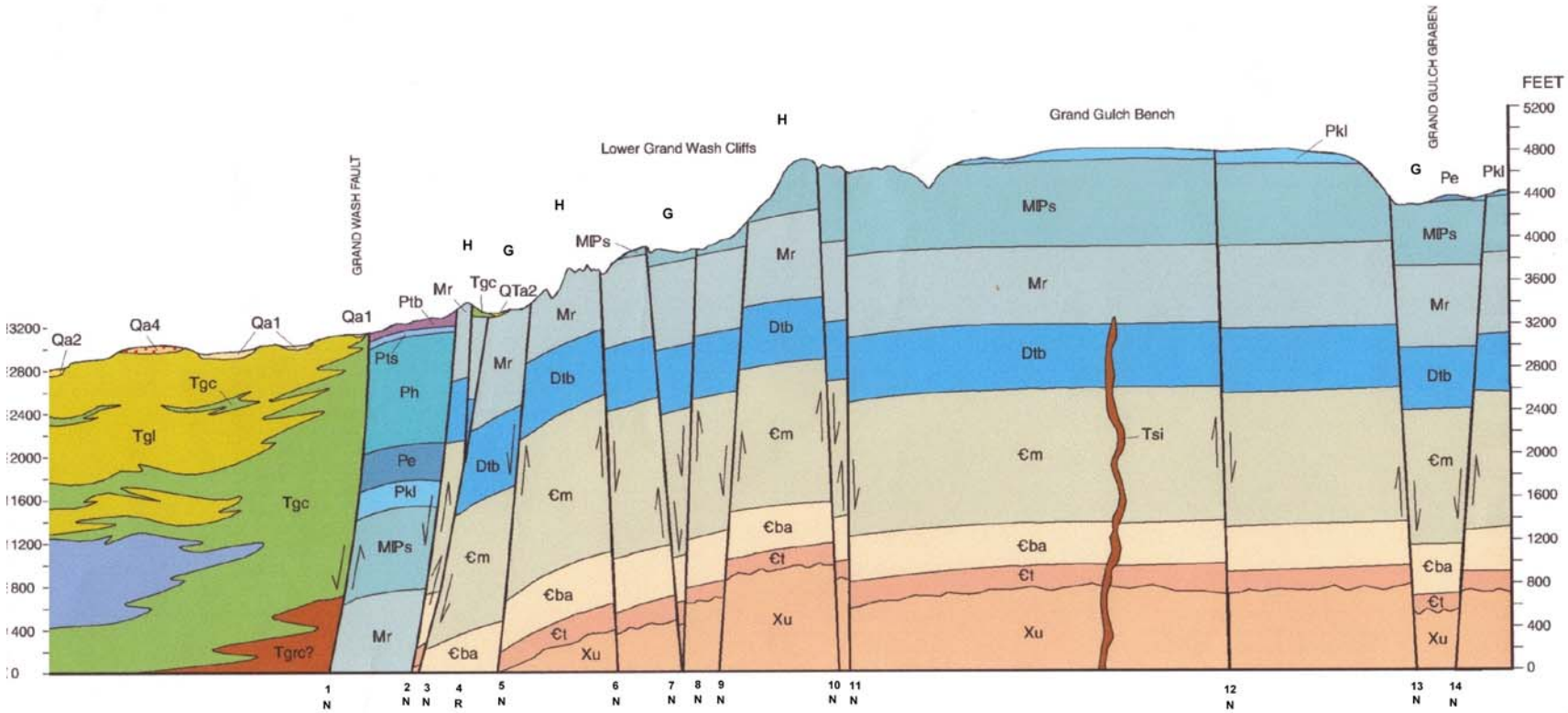
- ⇒ The top level of the section is the ground surface. It's a topographic profile.
- ⇒ Rock units is a general term – some units are sediments (young and not cemented) and others are many millions of years old.
- ⇒ Vertical exaggeration 2X means that 5200 vertical feet is 2600 horizontal feet. The section is about 5800 feet wide (about one mile).
- ⇒ Zero on the vertical scale is sea level.
- ⇒ The relative positions of units are more important than the Era, Period, Epoch, or ages in millions of years. That is just extra information about the rocks and sediments.
- ⇒ The cross-section itself is an interpretation. Geologists had to interpret the evidence of faulting at the surface and infer what happened beneath the surface.
- ⇒ The edges of the units to the west of the Grand Wash Fault are not folds, but facies, which show changes in sediment horizontally.
- ⇒ Unit Xu is the ancient crystalline basement rock (metamorphic and igneous).

Answers to questions are provided below. An annotated version of the cross section follows.

1. Fourteen faults are visible.
2. Numbered from left to right, the only reverse fault on the section is number 4 (found just below the letters “Tgc”.
3. There are three grabens.
4. There are three horsts.
5. Fault 1 (Grand Wash Fault) has the greatest vertical displacement. Unit Ptb on the right side of the fault is not visible on the left side of the fault, so it must be dropped down below sea level.
6. The minimum amount of vertical displacement on the Grand Wash Fault is 3100 feet.
7. The elevation of the top of rock unit MPs on the eastern side of the section is 3950 feet.
8. The elevation of the top of unit MPs on the western side of the section, adjacent to the Grand Wash Fault, is about 1500 feet.
9. The change in elevation of unit MPs from west to east is 3950 feet – 1500 feet = 2450 feet.

Challenge Question:

There is a greater thickness (1700 feet) of strata above MPS just east of the Grand Wash Fault and little to no thickness of those rocks to the east because uplift exposed them to erosion on the east.



Answer key showing fault numbers, types, and locations of grabens and horsts.

Cross section from: Billingsley, G.H., Beard, L.S., Priest, S.S., Wellmeyer, J.L., and Block, D.L., 2004, Geologic map of the Lower Grand Wash Cliffs and vicinity, Mohave County, northwestern Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-2427, scale 1:31,680, 17 p. [http://pubs.usgs.gov/mf/2004/mf2427/]

EVALUATE

1. Tensional stress (normal faults), compressional stress (reverse faults), and shear stress (strike-slip faults)
2. Answers should include bending an object like a pencil, piece of uncooked spaghetti, twig, etc.) as ductile stress and when it breaks, the object behaves like a brittle solid.
3. Where two plates collide, compressional stresses occur, and compression is more likely to fold rocks than tensional stress.
4. Faults played a bigger role in creating the landscape at Parashant because they help to elevate the land. Folds are small and limited to local sinkholes.
5. The person shown in Figure 6.11 is pointing to a fault. The angle of the fault is from upper right to lower left. Is this a reverse fault or a normal fault? Explain your decision.
6. Rocks break during brittle deformation. The blocks of rock look like they were fractured, forming joints.

LESSON 6: GEOLOGIC STRUCTURE AND THE PARASHANT LANDSCAPE

ENGAGE

Look at Figure 6.1. Sedimentary rocks at Parashant came from sediments deposited in nearly flat continuous layers.

1. Are the layers in Figure 6.1 lying flat?
2. Are the layers continuous (can you trace a single layer all the way across the photo)?
3. What do you think happened to these rocks since they first formed?

FIGURE 6.1. What do you notice about these layers of sedimentary rock near Mt. Logan at Grand Canyon-Parashant? Width shown is about 100 meters.

Write down your ideas. Discuss your ideas with a partner and the rest of the class.

EXPLORE

How do solids respond to forces that put them under stress? In the following activities, you will model forces that deform and break rock layers. These forces have played a key role in shaping the landscape at Parashant.

Part A: Modeling Stress and Strain

How many basic kinds of stress are there? Do rocks respond differently when different stresses are applied?

1. From your teacher, obtain a 12-ounce block of modeling clay (from Lesson 5), a plastic bottle cap, a sheet of waxed paper, and a metric ruler.
2. Form a rectangular solid out of the modeling clay roughly 9 cm by 4 cm by 4 cm. Start by rolling the clay into a cylinder about 9 cm long. With the clay in your hands, form four roughly flat faces. Flatten the surfaces by pressing each one down onto the table. Flatten the ends by pressing them into the table as well.
3. Lightly press the open end of a bottle cap into the center of one of the long flat surfaces, to make a circle. With a pencil tip, carve two perpendicular lines inside the circle, as shown in Figure 6.2.

4. The circle you have made will allow you to see how the clay model responds when forces are applied to it. **Stress** is a force applied to rocks. **Strain** is how the rock responds to stress, usually a change in shape or volume. Measure the diameter of the circle with a metric ruler. Draw your circle on a sheet of graph paper, to scale. Label this drawing "Side view: Original shape". You do not need to draw the entire model – just the circle and cross-lines. You can use the bottle cap to trace the circle.

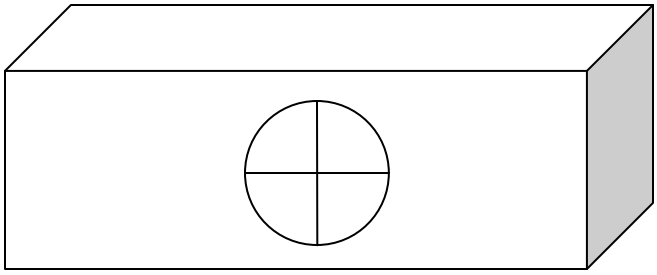


FIGURE 6.2. Diagram of clay model with reference circle and cross-lines.

5. Subject the rock to **compressional stress** by pushing the long ends of the model towards each other with your palms. Compress the model until it is half of its original length.

6. Record the strain on the model by measuring the lengths of the two cross lines and drawing a diagram of the new shape of the circle. Be sure to show any change in the angles between the two cross lines (they began as nearly right angles to each other). Draw large arrows pointing inward from the sides to show the compressional stress. Label this diagram "Side view: Shape after compressional stress".

7. Reshape the clay into a rectangular solid again. Try to make the clay about the same length and width as the original (9cm by 4cm by 4cm). Use the bottle cap and pencil tip to make the circle and two perpendicular cross lines on the side.

8. Subject the model to **tensional stress** by pulling on the clay lengthwise. Hold the clay in your hands like you would a sandwich and pull slowly, holding it firmly as you pull. Stretch the clay to about twice its original length without tearing it in two.

9. Record the strain on the model by measuring the lengths of the two cross lines and drawing a diagram, as before. Draw large arrows pointing outward (away from) and parallel to the circle. Label the arrows "tensional stress" and label the diagram "Side view: Shape after tensional stress".

10. Reshape the clay into a rectangular solid one more time, with the same dimensions as before. Carve the reference circle and two cross lines.

11. Draw a new diagram of the original shape because this time, you are going to focus on what happens to the top of the model. Label this drawing "Top view: Original shape".

12. Model how the clay responds to **shear stress**. To do this, lay the model on its side so that the circle is facing up. With your hands on each end of the model (like holding a sandwich), move your left hand towards you and your right hand away from you. Do this until the top of the left-hand side lines up with the bottom of the right-hand side. Stop before the clay breaks or tears.
13. Record the strain on the model, measuring and drawing, as before. Label the diagram "Top View: Shape after shear stress". Draw large arrows to show the direction of the stress – the directions in which you moved each hand.
14. In your own words, summarize the strain of the model in response to each kind of stress: compressional, tensional, and shear.
15. Put materials away and wash your hands.

Part B: Modeling Folds and Faults

How do rocks respond to stress? Stresses within the Earth strain or deform rocks. When deformation is ductile, rocks bend without breaking, forming folds. When deformation is brittle, rocks break, forming joints or faults. In this activity, your group will model and study a type of ductile or brittle deformation, then present your model to the rest of the class.

Table 1. Results of Modeling Stress and Deformation of Rocks

Structure	Stress: Compressional, tensional, or shearing	Deformation: Brittle or Ductile	Diagram: (Label Top or Side View; Use arrows to show directions of stress)	Explanation
A. Anticline				
B. Syncline				
C. Monocline				
D. Normal Fault				
E. Reverse Fault				
F. Strike-Slip Fault				

A. Anticline

1. Obtain a large piece of modeling clay (from Part A) and two smaller pieces of clay of different colors (use scraps from earlier lessons).
2. Divide the large piece of clay into three equal pieces. Flatten them into rectangular shapes about 9 cm long. Flatten the two smaller pieces into rectangles as well. It is okay if they wind up thinner than the larger pieces.
3. Stack the five layers, alternating colors.
4. Use a piece of dental floss to slice a clean face off of the long side. The end result should be a clean, flat surface 9-cm long when viewed from the side.
5. Holding the ends of the clay, press your hands together while pushing up a little with your thumbs to make a fold that points upward (an upside-down U).
6. Fill in the information in the correct row of Table 1, including a diagram of the side view of the model.

B. Syncline

1. Follow the same procedure for an anticline, but press down a little with your fingers to make a fold which points downward, like a “U”.
2. Fill in the information in the correct row of Table 1, including a diagram of the side view of the model.

C. Monocline

1. Obtain a large piece of modeling clay (from Part A), a smaller piece of clay of a different color (use scraps from earlier lessons), a thin textbook (or wood block), and a piece of dental floss.
2. Divide the large piece of clay in two equal parts. Shape the three pieces of clay into rectangular shapes 6cm wide by 9cm long.
3. Stack the three layers, alternating the colors.
4. Use a piece of dental floss to slice a clean face off of the long side. The end result should be a clean, flat surface 9-cm long when viewed from the side.
5. Lay a thin flat book (or wood block) on the table. Drape the model

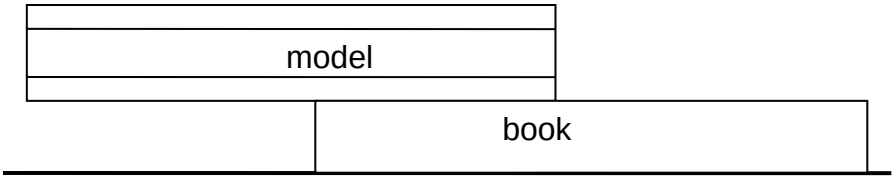


FIGURE 6.3. Set-up of the monocline fold model.

across the book lengthwise so that half of the model is hanging off (see Figure 6.3).

6. Put the palm of your hand on the book-side of the model. With your other palm, press straight down on the overhanging side until it is flat against the table. This will create a fold across the edge of the book, like a stair step.

7. Fill in the information in the correct row of Table 1, including a diagram of the side view of the model. Note: Although you pressed one side of the model down to form the fold, the book also pushed upward on the other side of the model. Use arrows to show both directions of stress on your diagram.

D. Normal Fault

1. Obtain a large piece of modeling clay (from Part A), two smaller piece of clay of a different color (use scraps from earlier lessons), a dropper bottle of liquid soap, and a piece of dental floss.

2. Divide the large piece of clay in two equal parts. Shape the three pieces of clay into flat rectangular shapes 4cm by 4cm by 9cm.

3. Stack the five layers, alternating the colors.

4. Turn the model on its side so that you look down on the layers. With a piece of dental floss, slice the model at a 45 degree angle from upper right to lower left (see Figure 6.4). This slice is called the **fault plane**.

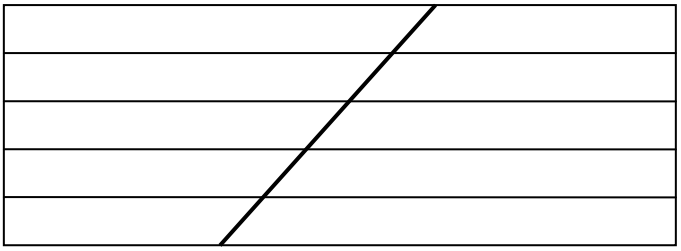


FIGURE 6.4. Side view of model showing fault plane (heavy line).

5. Separate the two sides of the fault and put a drop of liquid soap on the fresh surfaces you have just sliced (the fault plane). This will prevent the clay from sticking and make it easier for sides of the model to slide along the fault.

6. Holding the model in your hands, pull the model apart, sliding the left side of the model down the fault plane, and the right side of the model up the fault plane.

7. Fill in the information in the correct row of Table 1. In your diagram of the side view of the model, include large arrows showing the direction of stresses (the directions in which you pulled) and small arrows to show the movement of layers on each side of the fault plane.

E. Reverse Fault

1. Follow the same procedure for setting up a normal fault. Instead of pulling the model apart, push the model together, sliding the left side of the model up the fault plane and the right side of the model down the fault plane.
2. Fill in the information in the correct row of Table 1. In your diagram of the side view of the model, include large arrows showing the direction of stresses (the directions in which you pulled) and small arrows to show the movement of layers on each side of the fault plane.

F. Strike-slip Fault

1. Obtain a large piece of modeling clay (from Part A), two smaller piece of clay of a different color (use scraps from earlier lessons), a dropper bottle of liquid soap, and a piece of dental floss.
2. Divide the large piece of clay in two equal parts. Shape the three pieces of clay into flat rectangular shapes 4cm by 4cm by 9cm.
3. Stack the five layers, alternating the colors.
4. With a pencil tip, carve a light groove down the length of the top layer (see Figure 6.5).
5. With a piece of floss, slice the model from top to bottom vertically (see Figure 6.5).

FIGURE 6.5 Top view of strike-slip fault model. Light line shows the groove. Heavy line shows the fault line.

6. Separate the two sides of the fault and put a drop of liquid soap on the fresh surfaces you have just sliced (the fault plane). This will prevent the clay from sticking and make it easier for sides of the model to slide along the fault.
7. Looking down on the model, push the right side of the model “north” (away from you) and pull the left side of the model “south” (towards you).
8. Fill in the information in the correct row of Table 1. In your diagram of the top view of the model, include large arrows showing the direction of stresses (the directions in which you pulled and pushed) and small arrows to show the movement of the layers on each side of the fault.

EXPLAIN

Comparing Clay Models to Real Structures

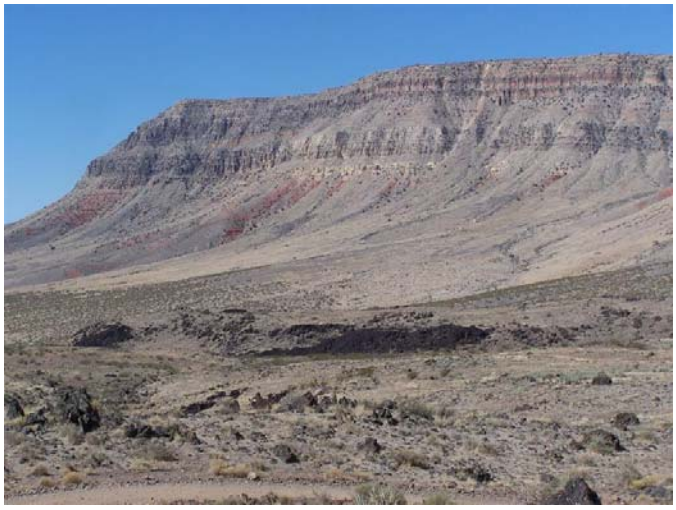


FIGURE 6.6 Rocks exposed here at Parashant are the uplifted block of a normal fault. The downthrown side on the valley floor has been buried by sediments (alluvium).

Clay models gave you a chance to think about how the rock layers shown in Figure 6.1 came to be deformed. But processes in nature are often more complex than our simple physical models. Let's look at ways that rocks and stresses are similar to and different from the clay models.

The force you applied to move the clay simulated stress on rocks. In nature, these forces arise when huge plates of Earth's crust and upper mantle meet (often very far away). Plates meet three different ways. In general, plate collision produces compression, separation causes tension, and plates that slide past one another horizontally cause shear. Geologists group all three as **tectonic stresses**. One kind of stress can produce another kind. For example, plate collision in the western US peaked between 65 and 50 million years ago. When the Pacific (oceanic) plate dove at a low angle beneath the continental North American Plate, it caused shear stress in the lower crust. Shearing then caused compression in the upper crust, sending rocks upward to form the Rocky Mountains.

Time, heat, pressure, and the thickness of rock layers also control rock deformation. Unlike the clay model that you held in your hands, rock is buried in the Earth (until it is brought to the surface by tectonic forces or erosion, which strips away overlying material). Burial makes rock hot and puts it under great pressure due to the weight of the rocks above it. Heat and pressure applied over a long time make the rock more likely to deform by flowing and folding. A sitting bench made out of a piece of Kaibab Limestone would shatter when hit with a heavy hammer, but would sag under its own weight over time. Rock that is cooler, under less pressure (closer to the surface), and stressed rapidly tends to deform by breaking (fracture). Obviously, you ran your models and stress tests with different materials under very different conditions than what is found within the Earth, but the general concepts apply.

A final comparison is that your models focused on folding and faulting separately. In nature, the forces that create faults can also create folds. Rock may also begin to flow and fold and then suddenly break to form a fault. In your models, you sliced the clay to make a fault. This was done so that you could focus on the specific type of feature that forms. If you were to try to create the fault without

slicing the clay, you would see the clay begin to flow and fold prior to faulting. In sum, even though the processes that deform rocks are more complicated and can take millions of years, your models showed the basic kinds of structures that forces in the Earth create.

Brittle Deformation – Joints, Faults, and Earthquakes

When rock behaves like a brittle solid, it fractures. Fractures include joints and faults. Anytime a solid breaks or cracks, it becomes weaker. This allows water to seep in more quickly and can be a passageway through which magma reaches the surface.

FIGURE 6.7 Nearly vertical joint in an ancient sand dune (sandstone) at Parashant .

Joints are fractures in rock along which very little movement has occurred (see Figure 6.7). Have you ever seen mud cracks that form after muddy water has evaporated? The cracks in the mud are like joints in rock. Some joints are made by tectonic stress. Cooling of magma or lava also causes stress that can create joints. As the magma or lava cools, it shrinks or contracts. The basalt columns shown in Figure 6.8 formed when cooling caused joints to form polygons Joints can extend for miles in rock. Weathering makes them wider over time, creating spectacular landscape features. Canyons, arches, natural bridges, pinnacles, and columns are examples of features largely controlled by joints.

FIGURE 6.8 Joints in this columnar basalt formed due to stress as lava cooled and contracted.

Faults are fractures in rock along which vertical or horizontal movement (or both) has occurred. The surface formed by the break is a zone of weakness called a **fault plane**. Once a fault forms, rocks along it will continue to deform as long as stress is applied. The rocks continuously store the energy built up by stress. If the releases its stored energy suddenly, we feel the vibrations as an **earthquake**. Faults can remain inactive for millions of years, only to be renewed by renewed stress.

FIGURE 6.9 Fault at Parashant (fault outlined in black). Is this a normal or reverse fault?

As you learned in Part B of the activity, the type of stress applied influences the type of fault that forms. At a basic level,

compression creates reverse faults and thrust faults (low angle reverse faults with lots of horizontal motion), extension causes normal faults, and shear causes strike-slip faults. Of course, forces and stresses in nature are more complicated. Faulting can go hand-in-hand with folding. Faults vary in age, length, amount and frequency of movement, and depth, with some faults extending for hundreds of miles along the surface. An example of this complexity will be discussed below in the section on geologic structure at Parashant.

Ductile Deformation - Folds

Folds form when rocks respond to stress by ductile deformation. It may be difficult to think about solid rocks flowing like a stick of warm taffy held in your fingertips. But remember, rocks are warmer inside the Earth, and stress is applied very slowly, over millions of years. This enables rocks to bend before other forces bring the folded layers to the surface for us to see. Folds range in size from microscopic to kilometers (see Figure 6.10). They often result from compressional stress. Large-scale folding is often evidence of plate collision. The intricate ribbon-like pattern of anticlines and synclines that make up part of the Appalachian Mountains formed when the North American Plate slammed into the Eurasian Plate more than 200 million years ago.

FIGURE 6.10 A small monocline in sedimentary rocks just north of Parashant.

Some folds are due to uplift. If sediment buries a thick layer of salt, the salt may become ductile enough to flow upward dome the layers above. Large bodies of magma that rise upward also form domes. Monoclines are one-sided folds that can form when sedimentary rocks are draped over deeper faults in basement rock, like a rug draped over a step (or your clay model draped over a book!).

Major Geological Structures at Parashant

What do Mt. Everest and Parashant have in common? More than you might think! For one, limestone that formed from marine sediments now caps both Everest and Parashant's Kaibab Plateau. Colliding plates played a big role in shaping the geological structures of both places. To understand how the landscape of Parashant formed, it helps to start by thinking about its elevation and the types of rocks that make up the land.

The monument sits on the Colorado Plateau, a large raised area of mostly desert land with an average elevation of 5000 feet above sea level. Elevations at

Parashant range from 1200 to 8200 feet. Smaller, flat or gently sloping plateaus made up of thousands of feet of sedimentary rock (and capped by lava flows in places) dominate its landscape. Rocks are tilted gently to the northeast. Stream erosion carved canyons into the plateaus, and volcanoes erupted lava many times. Beneath the sedimentary and volcanic rocks lie rocks that make up what geologists call the **basement**. At Parashant, basement rocks are metamorphic (gneiss and schist) and rocks that formed from cooling magma (igneous). Most of the strata on the monument, including the marine limestone called the Kaibab Formation that caps the eastern plateaus, came from sediments deposited under water. Further deposition buried these beds under thousands of feet of overlying deposits, turning them into rock. So why do we see them today atop plateaus? How can the landscape be so elevated and yet gently sloping? What happened?

It turns out that the geologic structures (mainly faults) within basement rocks have played a crucial role. Some 300 million years ago, the collision of plates that formed the ancient Rocky Mountains caused compression in the Colorado Plateau. The compression deformed and faulted Parashant's basement rocks. As mentioned earlier, once faults form, they remain as zones of weakness that later stresses can renew. And the Colorado Plateau has undergone several periods of major geologic stress in the past 300 million years. Scientists are still trying to figure out the history and causes of uplift of rocks in the Colorado Plateau. One thing that agree about is that the Plateau has acted like a rigid stable block (rather than being tilting severely or forming complex folds). In contrast, the land that surrounds the Plateau reacted differently to these forces and was pulled apart. The tensional stress led to normal faulting of the Basin and Range region west of Parashant. This activity continues today. The Plateau continues to rise, while faults remain active around the edges.

The interaction between plate collision and older basement faults left Parashant with a number of major north-south trending faults. These include the Grand Wash, Dellenbaugh, Shivwits, Main Street, Hurricane, and Toroweap Faults. The Grand Wash Fault makes the boundary for the west side of the Colorado Plateau. This spectacular normal fault has about 24,000 feet of vertical displacement! The Hurricane Fault extends for some 150 miles across northern Arizona and into Utah. Geologists believe that motion of the faults has shifted over time. That is, basement faults that began as normal faults changed direction during compression, causing reverse faults. Later, tectonic stresses produced normal fault motion. Several remain active today as normal faults. Traces of these faults are visible where they break through basalt flows and layers of sediment at the bases of cliffs, and minor earthquake activity occurs.

Some geological structures at Parashant came not from tectonic stress but arose due to the collapse of underlying layers. For example, many bowl-shaped depressions exist at the surface in the Kaibab Formation. The rock layers dip inward, but they are not tectonic folds. Instead, they are the surface features of column-shaped **breccia pipes** that form when groundwater dissolves older limestone below the Kaibab rock layers. The breccia pipes also become conduits for fluids that concentrate minerals like uranium and copper. The dissolution of

gypsum layers in the Kaibab Formation also creates sinkholes and minor folds on several plateaus within the monument.

ELABORATE

In this activity, you will interpret a cross-section (side-view) of the western side of Parashant that shows the Grand Wash Fault. The legend explains the symbols on the section that indicate the ages and names of rock units. All but two units are sedimentary rocks or sediments. To interpret the cross-section, assume that most of the sedimentary rocks were once lying flat in continuous layers. The vertical scale of the section is twice that of the horizontal. This makes faults and slopes look steeper. The faults are not vertical, so you should be able to tell a normal fault from a reverse fault.

1. How many faults do you see?

2. Number each fault from west to east. Place the numbers below the bottom of the faults.

3. Based upon the inclination of the fault and the positions of rock layers on either side of the fault, identify the faults as normal faults or reverse faults. Below each number, write an N for a normal fault and an R for a reverse fault.

4. Grabens are lowered blocks bounded by two normal faults. How many grabens can you see? Label each graben with a G.

5. Horsts are raised blocks bounded by two normal faults. How many horsts can you see? Label each horst with an H.

6. Which fault has the greatest vertical displacement? How do you know?

7. Based upon what you can see in the cross-section, what is the minimum amount of vertical displacement on the Grand Wash Fault?

8. What is the elevation of the top of rock unit MPs on the eastern side of the section on the Grand Gulch Bench?

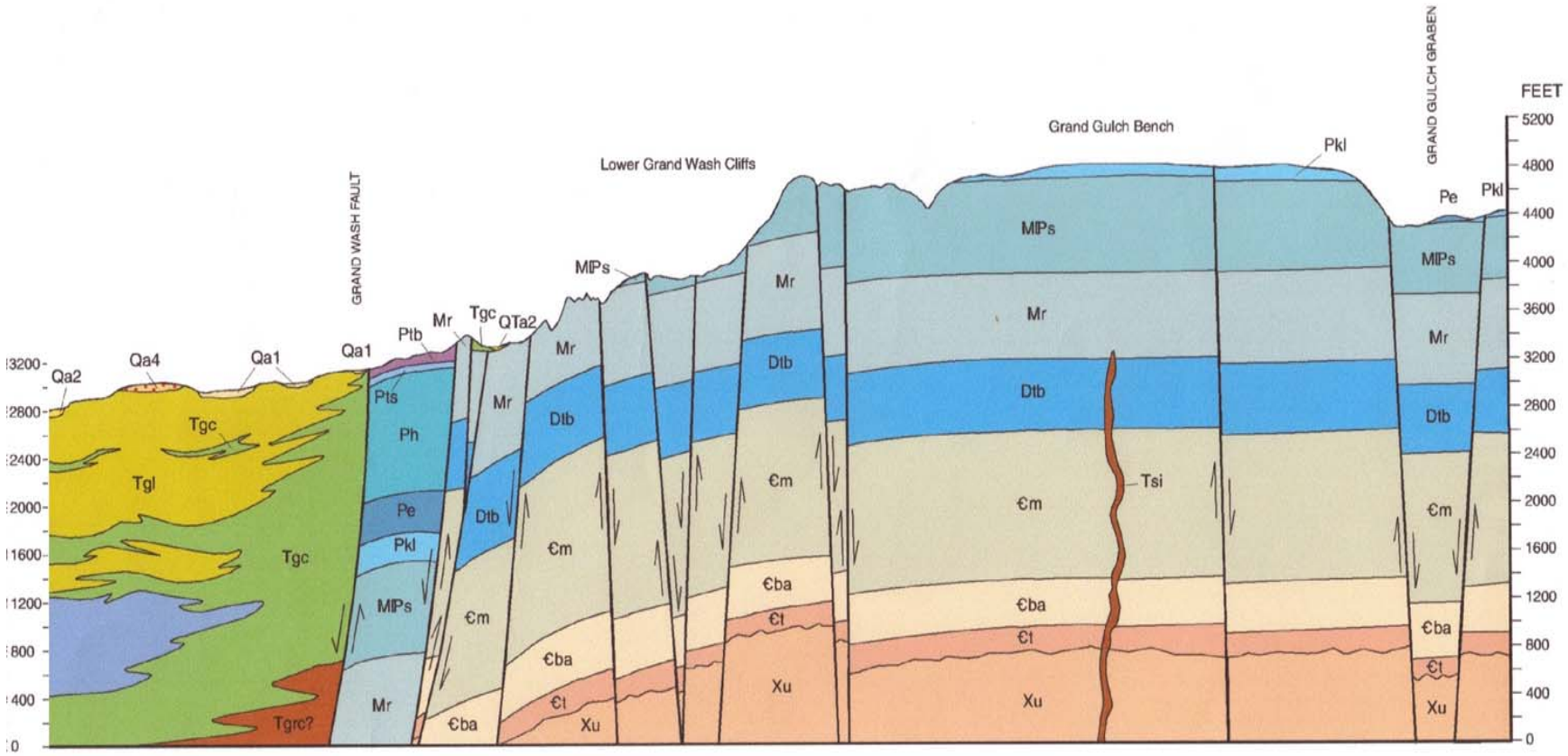
9. What is the elevation of the top of unit MPs on the western side of the section, adjacent to the Grand Wash Fault?

10. What is the change in elevation of unit MPs from west to east between those two locations?

Challenge Question: The higher the elevation of the landscape, the more likely it is to be eroded. What evidence do you see in the cross-section to support this claim? Hint: Use the units that lie above Unit MPs as a guide.

Legend for the Cross Section through Grand Wash Fault

Era Million years ago	Period	Epoch	Symbol	Rock Unit
Cenozoic 65-present	Quaternary	Holocene	Qa1	Youngest alluvial fan deposits
		Pleistocene	Qa2	Young alluvial fan deposits
			Qa4	Old alluvial fan deposits
			QTa2	Intermediate alluvial fan deposits (Pleistocene or Pliocene?)
	Tertiary	Pliocene	Tsi	Dikes and Necks (igneous intrusions)
		Miocene	Tgl	Limestone and siltstone facies
			Tgg	Gypsum and gypsiferous sitstone facies
			Tgc	Red Paleozoic clast conglomerate facies
			Tgrc	Grey Paleozoic clast conglomerate facies
		Oligocene		
		Eocene		
		Paleocene		
Mesozoic 248-65	Cretaceous			
	Jurassic			
	Triassic			
Paleozoic 543-248	Permian		Ptb	Toroweap: Brady Canyon Member
			Pts	Toroweap: Seligman Member
			Ph	Hermit Formation
			Pe	Esplanade Sandstone
			Pkl	Pakoon Limestone
	Penn-Miss.		MPs	Lower Supai Group
	Mississippian		Mr	Redwall Limestone
	Devonian		Dtb	Temple Butte
	Silurian			
	Ordovician			
	Cambrian		Cm	Muav Limestone
			Cba	Bright Angel Shale
			Ct	Tapeats Sandstone
Proterozoic 2500-543			Xu	Crystalline Rocks (basement)
Archean 3800-2500				
Hadean 4500-3800				



Vertical Exaggeration ~2X

Cross section from: Billingsley, G.H., Beard, L.S., Priest, S.S., Wellmeyer, J.L., and Block, D.L., 2004, Geologic map of the Lower Grand Wash Cliffs and vicinity, Mohave County, northwestern Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-2427, scale 1:31,680, 17 p. [http://pubs.usgs.gov/mf/2004/mf2427/]

EVALUATE

1. Describe the three kinds of stress on rocks and name the types of fault that each commonly produces.
2. Use a common everyday object to illustrate stress produces brittle versus ductile deformation.
3. Why is folding more common where two plates collide than where two plates separate?
4. What type of deformation is more important in producing the Parashant landscape – folding or faulting? Explain.
5. The person shown in Figure 6.11 is pointing to a fault. The angle of the fault is from upper right to lower left. Is this a reverse fault or a normal fault? Explain your decision.
6. Look at the blocks of conglomerate shown in Figure 6.12. The largest blocks are 2 meters across. Are the blocks the result of brittle or ductile deformation? Explain.

FIGURE 6.11 Fault in Mesozoic strata north of St. George, Utah.

FIGURE 6.12 Blocks of the Shinarump Conglomerate near Snow Canyon State Park, Utah.