

## **Flat Shoals Creek Outcrop of the Hogan Creek Formation: A Teaching and Activity Guide for High School and Undergraduate Students**

### **Location:**

The outcrop is located at the Sunset Park Campground, N 36.39790, W 80.19300, off NC 89/8 just south of Danbury, NC; the address is 1070 Sunset Park Rd Danbury, NC 27016. Owner Alan Bullins (gabull62@aol.com, 336-593-2992) graciously welcomes geologists. Park just east of the office, continue walking over the bridge, and turn left at a dirt road along Flat Shoals Creek and follow it to the outcrop.

### **Introduction**

Over a billion years ago, the supercontinent Rodinia formed by continents colliding in the Grenville orogeny. Later, tectonic rifting split the continents up, and the Iapetus Ocean formed off the coast of what is now North America. Many of the rocks of the Sauratown Mountains were originally deposited as sediments and document the rifting of Rodinia and the early evolution of the Iapetus Ocean. Rifting initially caused the development of localized basins (which filled with immature clastic sediments), plus rift-related igneous rocks. As the ocean grew, a passive margin (meaning no tectonic activity) gradually developed on the continent's eastern edge, and increasingly mature sediments were deposited. These rocks were deposited as sediments between 500 and 750 million years ago, then were deformed and metamorphosed during the Taconic Orogeny, approximately 460 million years ago.

### **General tectonic history:**

In the Sauratown Mountains window, we find rocks ranging in age from the Precambrian (1.1 – 1.2 billion years old) to the Early Cambrian. They were formed in a complex ballet of plate movement and collision, subduction and orogeny:

1. **Grenville Orogeny** (1.2 billion yrs ago): formation of supercontinent Rodinia
2. **Incipient rifting:** (begins 750 million years ago): The supercontinent begins to pull apart, rift basins begin to form & fill with sediments; rift-related igneous rocks form.
3. **Successful rifting:** (begins approx 620 million years ago) Rift basin develops into the Iapetus Ocean; igneous activity, deposition of increasingly mature marine sediments.
4. **Passive margin develops** 600 – 500 million years ago, with characteristic mature sediments (sandstone, shale, limestone).
5. **Taconic orogeny:** 460 million years ago. Subduction, metamorphism, plutonism; this is probably when the Piedmont Terrane continental sliver accreted onto the continent. This is when our sedimentary rocks reached their peak of metamorphism.
6. **Alleghenian orogeny:** 330 million years ago. Continent-continent collision, deformation, metamorphism, thrust faulting.

### The Sauratown Mountains window:

The Sauratown Mountains lie to the southeast of the Blue Ridge Mountains in northwestern North Carolina. These rocks were uplifted during the Alleghanian Orogeny, 330 million years ago, when continents collided to form Pangaea. The collision caused faulting, and stacked thin slices of crust called thrust sheets atop each other along almost horizontal thrust faults.

The area has been interpreted as a complex window. Broadly, the structure is that of a northeast trending arch composed of several stacked thrust sheets. The tectonic forces that caused the thrust faulting also folded these slices up into a large arch-shaped structure. In this area, erosion has cut through the rocks of the upper thrust sheets to produce a complex "window", giving a view of the rocks beneath the upper thrust sheets.

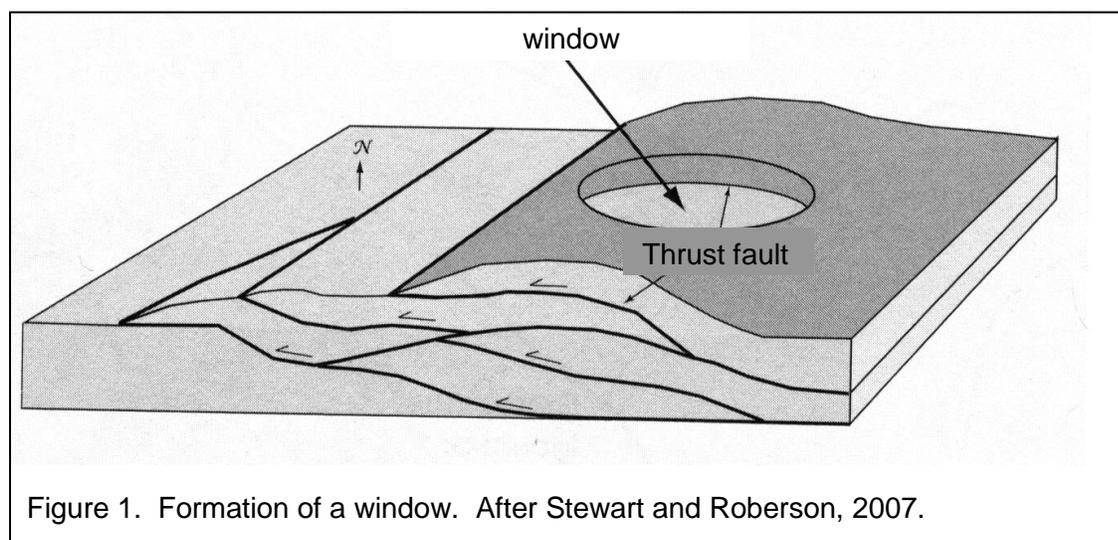


Figure 1. Formation of a window. After Stewart and Roberson, 2007.

Each thrust sheet shows a sequence of 1.1 – 1.2 billion year old Grenville-age crystalline basement rocks, overlain by Late Proterozoic to Early Cambrian metasedimentary rocks (Sauratown Formation, Hogan Creek Formation, and Ashe Formation) that document the Upper Proterozoic rifting of the supercontinent Rodinia and its development into a passive margin. The Ashe Formation protoliths were immature clastic sediments and volcanics, interfingered with rift basalts, deposited further from the continental margin and closer to the rift. The Hogan Creek's protolith was rifted-margin deep water rocks, deposited closer to the continent and further from the rift than the Ashe. Sauratown Formation protoliths range from silts to sandstones, deposited as clean rift-facies sediments (shallow shelf to beach?) inboard of the Hogan Creek. The three formations probably formed at about the same time, just closer to or further from the continental margin.

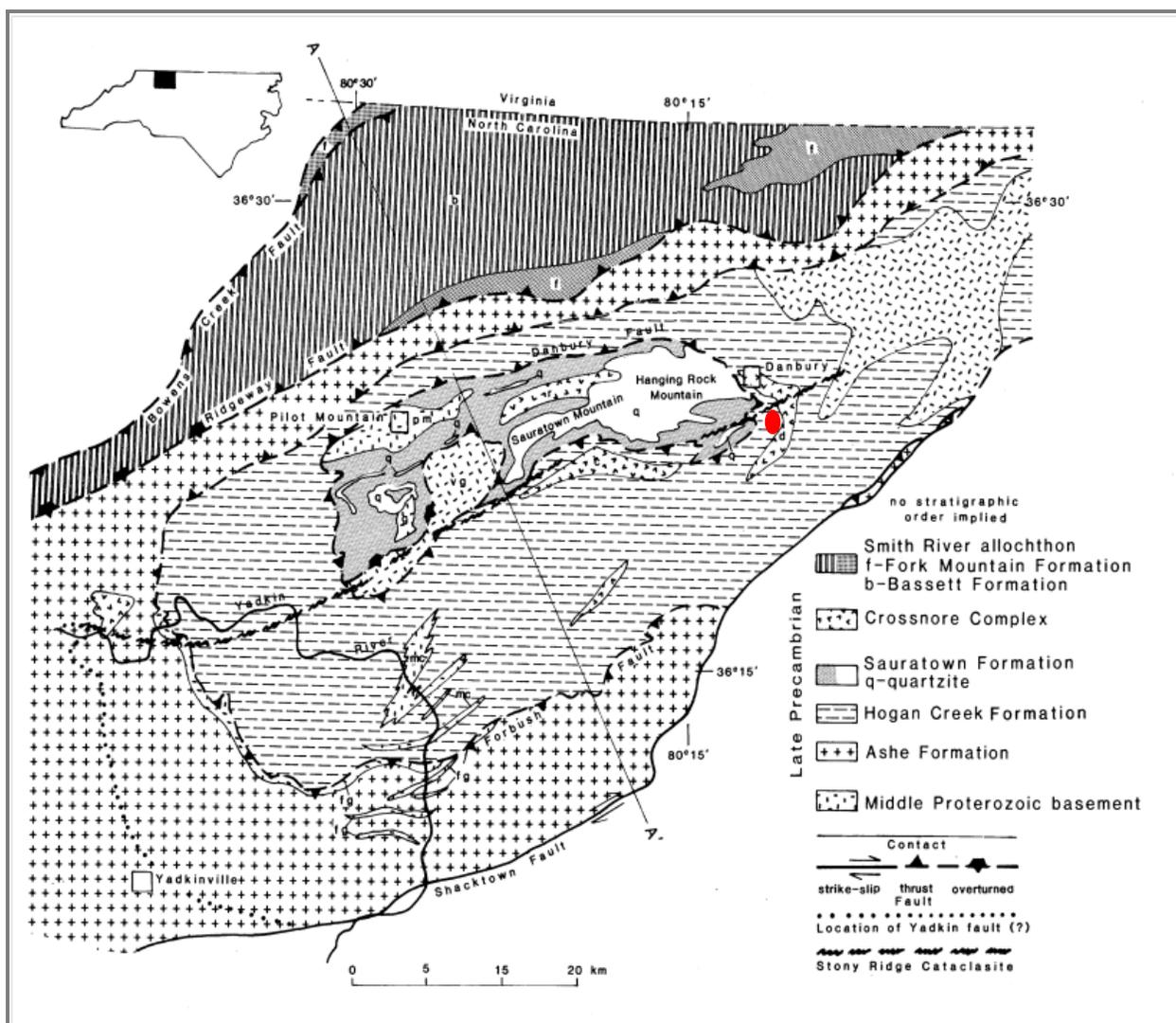


Figure 2. Generalized geologic map of the Sauratown Mountains window (from McConnell, 1988). Red dot shows approximate location of the outcrop.

### The outcrop:

In this 60 x 10 meter outcrop of the Hogan Creek Formation, you can observe several different types of rocks. Remember these were deposited as sedimentary rocks, but have since undergone metamorphism. Even so, the trained eye can figure out a lot about what the parent rock would have been, based on chemical/mineral composition:

- Sandstone (from beach deposits) becomes quartzite or metasandstone.
- Mudstone (from clean deeper-ocean clay-rich sediments) becomes muscovite schist.
- Graywacke forms more mafic-rich metamorphic rocks—schists and gneisses with lots of biotite and not so much muscovite.

All of the rocks we see, listed below, have different mechanical properties.

**Biotite gneiss or schist:** Most of the outcrop is comprised of a fine-grained biotite-muscovite gneiss or schist (metagraywacke). This location is close to the Danbury thrust fault; many rocks in the area appear to show grain-size reduction and shearing as a result.

**Metasandstone:** Several thin (10 – 25 cm) layers of fine-grained metasandstone run along the length of the outcrop.

**Quartz-feldspar pods:** This outcrop contains many deformed pods, lenses, and irregular veins of coarser-grained crystalline quartz-feldspar+-mica. The pods look “granitic”, like migmatites formed by high grade anatexis or partial melting of a metamorphic source rock. Yet the metamorphic grade of the Hogan Creek Formation is no higher than garnet zone, while anatectic migmatites typically form at much higher metamorphic grades. Thus these pods likely formed by metamorphic differentiation, not by partial melting.

**Quartz veins** are also found cross-cutting the other rocks in this outcrop. These are later-stage hydrothermal veins.

The various rock types exhibit different types of deformation in response to the elevated temperatures and pressures that have affected the rocks in this outcrop over geologic time. Resistance to flow is a property called *competency*. A rock with low competence may readily flow and deform under certain pressure and temperature conditions; a more competent rock layer will be less likely to deform in a plastic manner and may exhibit little change or may break through brittle deformation instead. In boudinage (pinch and swell structures), the more competent layers will tend to tear apart into chunks and the less competent layers will ‘flow’ into the spaces in between. Similarly, when layers are folded, the more competent layers will often control the amplitude and wavelength of the folds and the more ductile material will flow into the hinges.

## Selected Geologic Features of the Flat Shoals Outcrop

We've included photographs and a guide to help you locate some of the more interesting features at the outcrop. This is not a completely inclusive list, so be sure to spend some time exploring the outcrop for yourself!



Figure 3. Panoramic view of the outcrop. Numbers refer to location of features mentioned below. Competency contrasts can be observed all over the outcrop. From left to right:



Figure 4: Flat Shoals Creek, showing a point bar and cut bank. Students can also observe stream processes on the walk along the creek to the outcrop.

Figure 5: Differential weathering in the metasandstone layers. Here students can see the three 10- 25 cm thick layers of metasandstone. The metasandstone is more resistant to weathering than the biotite muscovite schist or gneiss that comprises the bulk of the outcrop.





Figure 6: Deformed porphyroclasts in highly strained biotite-muscovite gneiss. The best exposure of these is near the left side of the outcrop, approximately 7 feet up the wall. Some of the porphyroclasts can be used to determine shear sense.

Figure 7: Quartz-feldspar pod within the sheared biotite gneiss that has separated into boudins, surrounded by deformed porphyroclasts. It is too high for students to readily measure, but can be used as an excellent example of competency contrasts: the pod has ruptured, while the more malleable gneiss flowed into the gaps formed between the boudins.

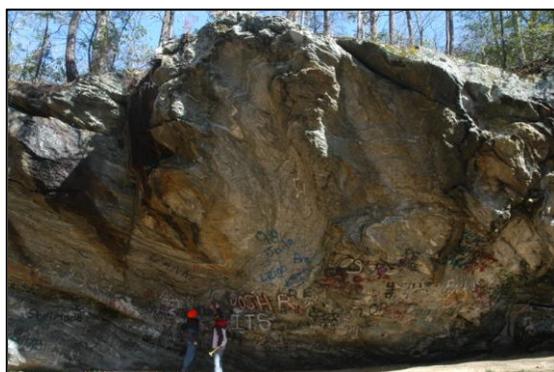


Figure 8: Where the students are standing by the graffiti-covered outcrop, the metasandstone beds dip below the surface of the ground. They reappear to the far right of the photo.

Figure 9: Highly deformed layers near the base of the outcrop, including inclined folds and dismembered sections. This is a good location to see how different rock types affect rheology. The quartz-feldspar vein is the more competent material, though there is some thickening in the fold hinges; the less competent biotite schist follows the form established by the light colored layer and is able to accommodate much tighter folding without rupturing. The more biotite-rich schist in the center of the synform in the upper left of the photo appears to be even less competent.





Figure 10: Close-up view of above and the different mechanical behaviors. Biotite-rich schist at the top; biotite-muscovite gneiss; quartz-feldspar vein. Note the cross-cutting hydrothermal quartz vein.

Figure 11: Dismembered quartz-feldspar pod surrounded by more malleable biotite gneiss. A very tight, nearly isoclinal fold in a metasandstone layer is shown in the upper right of the photo, above the green marker tape.



Figure 12 Rupture and offset of the fold limb in the quartz-feldspar pod above. This pod may demonstrate polyphase folding, as illustrated more clearly in another layer below (highlighted in yellow).



Figure 13: Far right side of outcrop. Metasandstone layers at bottom right.

Figure 14: Illustration of the effects of layer thickness on rheology. The thicker layers show longer wavelengths than the thinner layers.



Figure 15: In some parts of the outcrop, the thicker metasandstone units show no obvious shortening while thinner layers immediately above are distinctly folded.

Figure 16 Highly deformed and dismembered quartz-feldspar pods. Despite their igneous appearance, these quartz-feldspar pods are most likely to be formed by metamorphic differentiation, since the metamorphic grade of the Hogan Creek Formation is much lower than needed to see partial melting.



Figure 17: Close-up of quartz-feldspar pods.

Figure 18: Small reverse fault in one of the metasandstone layers near the base of the outcrop.



Figure 19: Folding in metasandstone layers near the base of the outcrop

## Teachers Guide for an In Class and Related Field Activity: Candy Bar Competency

It is recommended that students have some concept of rock properties such as competency prior to going out into the field. One strategy is to do a pre-trip activity during class time or as part of other laboratory exercises.

Learning Objective: Students should understand the concept that different rock materials deform in different ways, and can identify brittle vs. ductile deformation using an analog model (the candy bar)

Materials: Twix candy bars (preferably enough so each student can have their own. Snack sizes work fine!). The candy bars should be cold, but not frozen for best results.

Background: When rocks are heated and exposed to higher pressures during tectonic events, different types of rock behave in different ways. One property that can be observed in rocks is how much the rock has been deformed; maybe it has been folded, perhaps it was stretched into a very long thin layer, maybe it has been fractured, or perhaps it has been torn completely apart. The resistance to flowing (folding or stretching) is a characteristic called competency. A rock with low competence may readily flow and deform under certain pressure and temperature conditions; a more competent rock layer will be less likely to deform under these very same conditions, and instead may not change much at all or may break instead. In boudinage (pinch and swell structures), the more competent layers will tend to tear apart into chunks and the less competent layers will 'flow' into the spaces in between. Similarly, when layers are folded, the more competent layers will often control the amplitude and wavelength of the folds and the more ductile material will flow into the hinges. Thicker layers of the same material will often show less dramatic folding than thinner layers.

The Twix candy bar models different layers: the chocolate layer and the cookie layer are going to be brittle and break, but the caramel in the middle will deform and stretch in a ductile manner if students pull them apart slowly enough. The main concept to get across here is that rocks do the same thing: depending upon their composition, they may behave more like the 'caramel' or more like the 'cookie' under the higher pressures and temperatures they would have been subjected to during metamorphism and compression.

## Student Worksheet: Candy Bar Competency

### Introduction

When rocks are heated and exposed to higher pressures during tectonic events, different types of rock behave in different ways. One property that can be observed in rocks is how much the rock has been deformed; maybe it has been folded, perhaps it was stretched into a very long thin layer, maybe it has been fractured, or perhaps it has been torn completely apart. The resistance to flowing (folding or stretching) is a characteristic called competency. A rock with low competence may readily flow and deform under certain pressure and temperature conditions; a more competent rock layer will be less likely to deform under these very same conditions, and instead may not change much at all or may break instead. In boudinage (pinch and swell structures), the more competent layers will tend to tear apart into chunks and the less competent layers will 'flow' into the spaces in between. Similarly, when layers are folded, the more competent layers will often control the amplitude and wavelength of the folds and the more ductile material will flow into the hinges. Thicker layers of the same material will often show less dramatic folding than thinner layers.

In class activity

**Materials:** Twix candy bars, worksheet, pencil

**Objective:** You will be modeling rocks in a tectonic environment that is undergoing extension; this candy bar represents several rock layers that will undergo deformation in this environment.

1. At what type of tectonic boundary would you expect to see these types of stresses?
  
2. What do you think will happen to each of the layers as you begin to \*slowly\* pull apart your Twix bar?

Chocolate:

Caramel:

Cookie:

3. Now, slowly (!) pull apart your candy bar and pay attention to how the different 'rock' layers respond.

Draw a cross-section of the Twix bar in the space below, and label each layer (tasty chocolate, luscious caramel, delightful cookie). On your diagram, include some basic information on whether the layer exhibited elastic, ductile, or brittle deformation:

## Student Worksheet: Competency Observations in the Field

**Objective:** Identify structures in an outcrop that illustrate clear contrasts in competence under the elevated temperatures and pressures. At the Flat Shoals outcrop of the Hogan Creek Formation, there are several good examples of rock layers that have a higher competency than other rock layers.

Spend some time examining the four main rock types present in the outcrop (the metasediment layers, the biotite schist/gneiss, the “granitic” pods, and the quartz veins).

- (1) Record some notes below about each of the layers, paying special attention to the structures that you see for each of the rock types; do the layers end up forming faults or broken up pieces? tight folds? ‘squishy’ rounded folds? gentle folds? pinch-swell structures? does it look like the material ‘flowed’ into spaces formed when more competent layers were bent or broken?
- (2) For each rock type, include a sketch of at least ONE interesting structure that you see displayed in the outcrop

### Metasandstone:

### Biotite Schist/Gneiss:

**Quartz veins:**

**“Granitic” pods:**

(3) Based upon your observations, which layer(s) deformed in ways similar to the caramel in your Twix bar?

(4) Which layers sometimes behaved more like the cookie center of the Twix bar?

(5) Did any of the rock types that show a mix of characteristics, sometimes breaking and sometimes bending or flowing – if so, do you have any ideas for what might have caused it to break in some cases instead of bending?

## **Teachers Guide: Simple Quantification of Deformation (Elongation and Shortening)**

At the undergraduate level (particularly for the introductory courses) we do not usually worry about making sure the students measure in the 'best' direction of elongation or shortening unless it is very obvious. We focus more on getting them to realize that sedimentary rock layers or features were initially straight (or nearly so), and the folds or boudinage have caused a change in the overall length of those layers.

**Materials required:** Rulers, calculators

**Objectives:** Students will understand that rock layers can be stretched or shortened, and will be able to quantify the percent change.

**Key:**

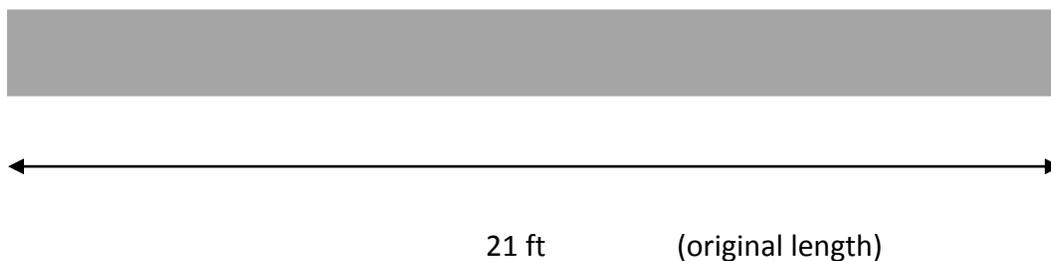
- (1) The elongation will be negative since the final length is less than the original length
- (2) The elongation will be positive since the final length is more than the original length
- (3)  $(15 \text{ ft} - 20 \text{ ft}) / 20\text{ft} * 100 = -25\%$
- (4)  $(10.0 \text{ cm} - 6.5 \text{ cm}) / 6.5 \text{ cm} * 100 = 53.8 \text{ cm}$  (or 54 cm)  
\*\*reproduction may change these measurements slightly

**Suggestions to incorporate field measurements from the Flat Shoals outcrop:**

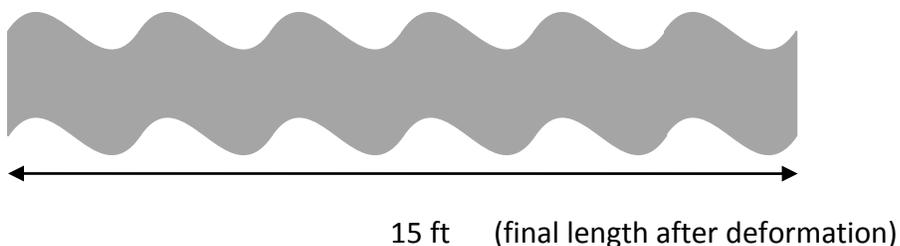
In the field you can have students measure elongation on various folds and other structures that are found throughout the outcrop. You can use a measuring tape, a flexible curve purchased at an office supply store, or just use string and a ruler to get estimates of original lengths for folds and for pinch and swell structures. Have students collect data from a variety of structures and compile the data. Quiz students on whether they think they should all of the elongations should be the same, or different; examine the results, and discuss reasons why some layers are more shortened than others, while still others exhibit elongation in the same outcrop!

## Student Worksheet: Quantification of Deformation (Elongation and Shortening)

When rocks deform, they can be stretched, compressed, or sheared. Some structures, such as folds, cause the layer to take up less straight-line distance than it did before the rock was deformed.



Above is an example of an undeformed rock layer, with an original length of 20 feet. After the rock is subjected to compressive forces at depth where it is hot enough to deform without breaking, the rock layer folds. The new straightline distance is now smaller, because the layer has been shortened.



In the field, we don't get to see that original length because the rock has already been deformed. We can sometimes estimate the original length by measuring along with the folds (dashed line below). This isn't perfect and we are making some assumptions about how the material has been distributed, but it gives us an estimate of that original length.



Length along the dashed path is 20 ft (estimate of the original length)

As you can see, we didn't get *\*exactly\** back to that true original value of 21 ft, but we got pretty close!



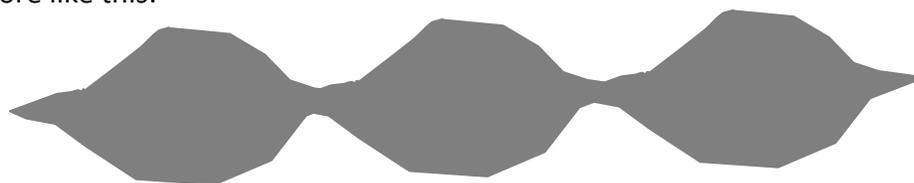
Another example of elongation is *boudinage* (also called 'pull apart' or 'pinch and swell' structures). In this case, a more competent layer is pulled apart and the softer material around it 'flows' into the gaps between. The word 'boudinage' means sausage in French, and it refers to the old style sausage links that are attached to one another by a thin string of casing material in between each individual sausage. Sometimes there is just a narrowing of the rock, and in others the rock breaks completely into separate sections:



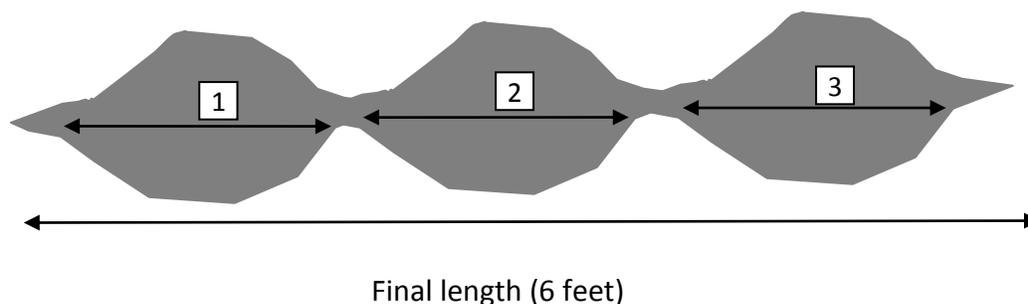
becomes



or could look more like this:



In this case, the original length can be estimated by measuring the length of each individual section and adding them all together (disregard the 'pinched' parts if present). This is easier if the sections behave in a brittle manner and are spaced apart.



Estimated original length = section 1 + section 2 + section 3 = 4.5 feet

(4) Determine the % elongation for the rectangular boudinage example pictured above (easiest if you measure using centimeters)

Additional resources:

- Hatcher, R. D. Jr., 1988, Sauratown Mountains window – Problems and regional perspective, *in* Hatcher, R. D. Jr., ed., *Structure of the Sauratown Mountains window, North Carolina, Guidebook*. Carolina Geological Society, p.1 - 19.
- Heyn, T., 1988, Geology of the hinge zone of the Sauratown Mountains anticlinorium, North Carolina, *in* Hatcher, R. D. Jr., ed., *Structure of the Sauratown Mountains window, North Carolina, Guidebook*. Carolina Geological Society, p. 20 – 50.
- Horton, J. W. Jr., and McConnell, K. I., 1991, The Western Piedmont, *in* Horton, J. Wright Jr., and Zullo, Victor, eds., *The Geology of the Carolinas: Carolina Geologic Society 50th Anniversary Volume*. Knoxville: The University of Tennessee Press, p 36 – 58.
- McConnell, K. I., 1988, Geology of the Sauratown Mountains anticlinorium: Vienna and Pinnacle 7.5 minute quadrangles, *in* Hatcher, R. D. Jr., ed., *Structure of the Sauratown Mountains window, North Carolina, Guidebook*. Carolina Geological Society, p. 51 – 66.
- Stewart, K. G., and Roberson, M., 2007, *Exploring the Geology of the Carolinas: A field guide to favorite places from Chimney Rock to Charleston*. Chapel Hill: University of North Carolina Press.