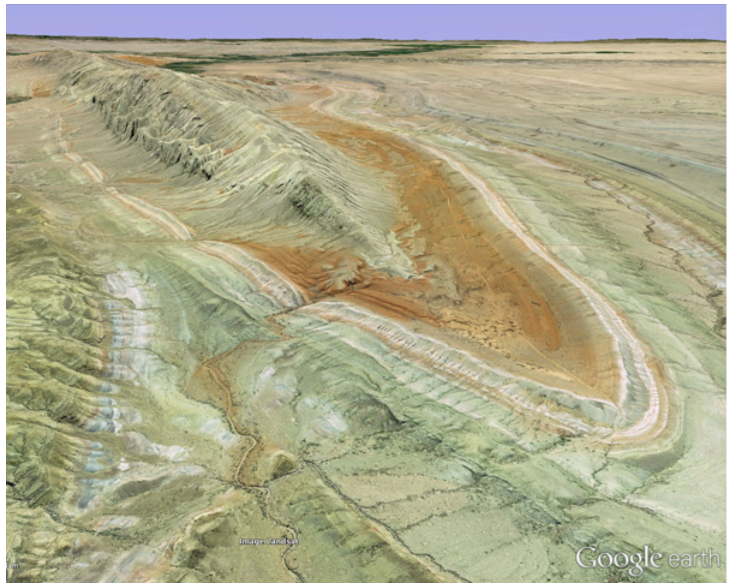
Fold Analysis Challenge
Sheep Mountain, Wyoming

Introduction



The Bighorn Basin area of Wyoming is well known for interesting and well-developed fold structures that also have economic significance - well over 1 billions barrels of oil have been produced from the Bighorn Basin since the early 1900s. These fold structures are well-exposed at the surface, and the lack of extensive vegetation coupled with the contrasting colors of different lithologies makes Google Earth a fabulous way to explore these structures in order to achieve a better understand of fold structures in general. At right, you'll see a view looking SSE across the nose of the spectacular Sheep Mountain Anticline, which we are going to explore in this exercise.

Getting started with Google Earth[1]

You will need either the Google Earth or Google Earth Pro desktop application. Google Earth for mobile devices is not adequate – you will need to use a desktop or laptop computer. If you do not have Google Earth on your computer, go to the free download site at http://www.google.com/earth/download/ge/, download Google Earth, and install it on your computer. If you already have Google Earth on your computer, make sure that it is updated to the latest version (but be sure to back up existing placemarks before you update!).

Once you have installed (or updated) Google Earth, launch Google Earth. In the main menu bar, go to Tools > Options (PC) or Google Earth > Preferences (Mac)

- Set the Terrain Quality slider to high and the elevation exaggeration to 1.
- Choose Decimal degrees for lat/lon, and meters/kilometers for showing elevation.
- The Options/Preferences may also have a check box called **Terrain**. If it does, make sure that there is a check mark in this box.
- Click on the Navigation tab, and choose "**Do not automatically tilt while zooming**."
- Go to Main Menu > View > Show Navigation > Always. Be sure that View > Status Bar and View > Scale Legend are checked as well.
- Go to the sidebar, and expand **Layers**. Turn off (i.e., un-check) **everything** except the Terrain box, if it's present. A terrain box is only present in Google Earth Pro, and you must be sure that there is a check mark in this box, or you won't be able to view terrain features in 3D.
- Collapse the row of photos to hide the photo tour at the bottom of the image screen.

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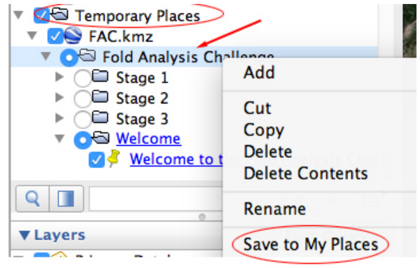
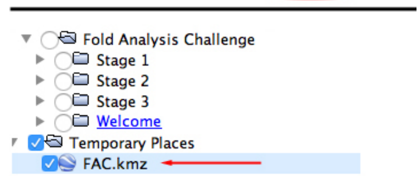
[1] If you are not already familiar with Google Earth, you can get help from: https://support.google.com/earth, including how to navigate with the mouse and arrow keys and to change viewpoint with shift and arrow keys.

Launching the Fold Analysis Challenge

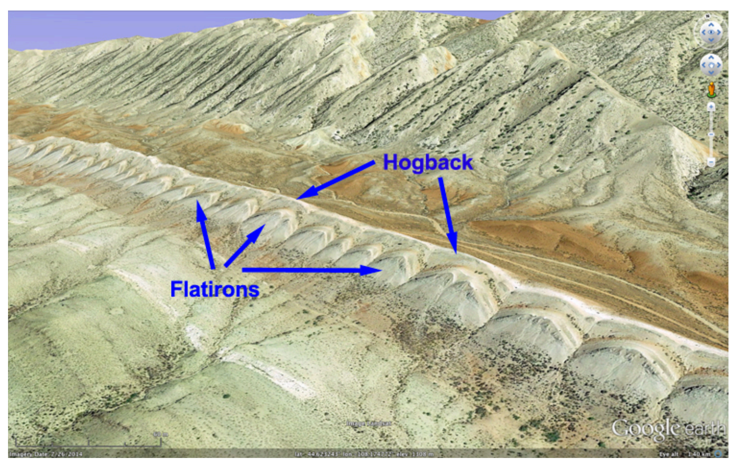
Download the Fold Analysis Challenge kmz file from http://www.geode.net/fac.kmz. Launch Google Earth, select Open from the File menu, and select the downloaded file, fac.kmz. The file will appear in the Temporary Places sidebar, and Google Earth will automatically zoom to the Bighorn Basin region of Wyoming. A welcome box will also appear when you load the file. Click the "x" to close it.

- Open FAC.kmz by clicking the down arrow if it is not already open. Right-click on the Fold Analysis Challenge folder, and choose **Save to My Places.** Once the Fold Analysis Challenge is in your My Places list, choose Save My Places from the main Google Earth menu. Delete FAC.kmz (the globe icon) from your Temporary Places.
- Expand the Fold Analysis Challenge folder in the side bar, but do **not** highlight any of the radio buttons.
- Double click on the word **Welcome** at the bottom of the list, and you will zoom in to Sheep Mountain. Close the white placemark description box in the image window.





The bedrock in this part of Wyoming consists of sedimentary strata that have been folded into anticlines and synclines. Take some time to zoom in and explore the area by tilting and flying through in 3D. The simplest way to do this is to put the cursor in the center of the screen, hold down the shift key, click and hold the mouse button, and drag to tilt and rotate. Anywhere you initially click the mouse will serve as the pivot point for tilting. Use the scroll wheel or navigation slider to zoom in and out. You can return to a vertical view with north at the top by pressing the **R** key.



You'll see that different sedimentary layers have different properties: different colors, different joint patterns, different resistances to erosion, different vegetation. You'll also see spectacular topographic features, including flatirons and hogback ridges.

Flatirons and **hogback ridges** are named for their resemblances to an old-style iron for ironing clothes and for the stiff ridge that sticks up on the back of a wild boar respectively (see pics lower right).

Once you are done exploring, double-click again on **Welcome** in the side bar to return you to a bird's eye view of Sheep Mountain. Close the welcome placemark description box.

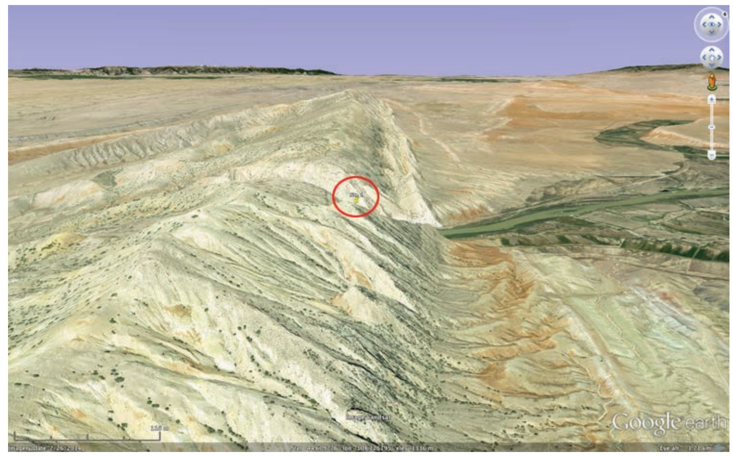
What is the Fold Analysis Challenge?

The purpose of the Fold Analysis Challenge is to help you visualize the orientations of the eroded sedimentary layers at various places around Sheep Mountain so that you can better visualize the shape and orientation of the fold structure responsible for the patterns that we can see in Google Earth. After you have worked with Sheep Mountain, you will apply what you have learned to interpret other fold structures in the Bighorn Basin. Once you have become adept at visualizing structures, you can use the same strategies for visualizing fold structures anywhere in the world where they are well exposed in Google Earth.

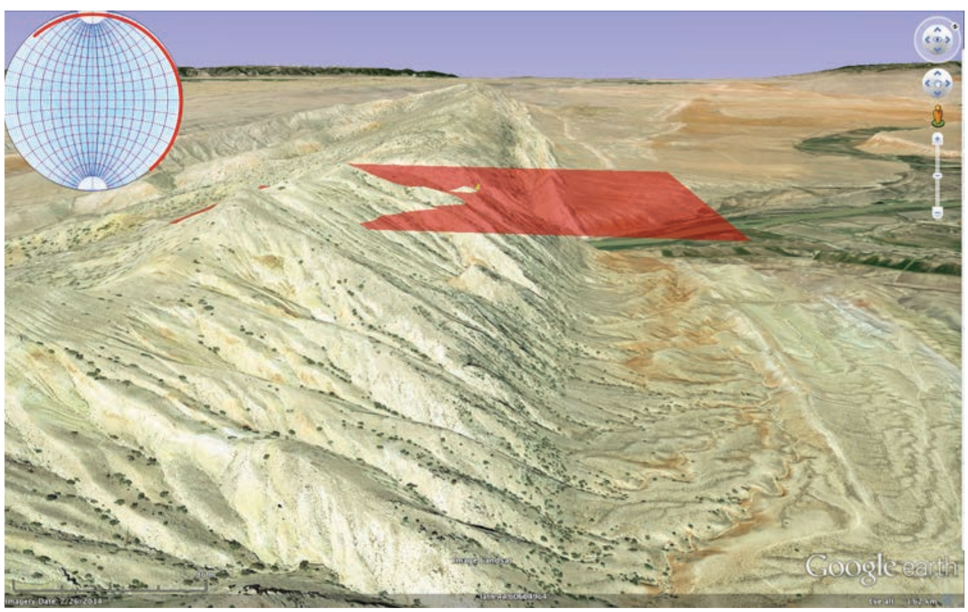
Stage 1

Determining dip. You first task will be to determine the orientation of the sedimentary layers at two sites roughly in the middle of the Sheep Mountain structure and determine the trend of the fold axis for that part of the fold.

- Double-click the Stage 1 folder to zoom you in to the correct location on Sheep Mountain.
- In the Google Earth sidebar, highlight **only** the **Site 1** placemark.
- Double-click the Site 1 placemark to fly you to Site 1. Tilt and rotate until you have the view shown at right.



- Highlight the radio buttons for the folders **Site 1 dips** and **Rotate Stereographic Net,** and a stereographic net and a translucent red plane will appear.



Expand the **Site 1 Dips** folder, and you'll see a series of numbers. Choose one of the values by highlighting its radio button. Try choosing several more. What happens to the translucent red plane in the image as you choose different values?

Now, choose a number of different values, but watch closely what happens to the stereographic projection. You'll see that the ***strike*** remains the same but the **dip** changes. The steeper the dip, the less pronounced the curvature of the great circle is on the stereographic projection.

Your job now is to find the dip value that rotates the red plane until it best matches the dip of the layers in Google Earth. You will need to examine the clues presented by the various bedding traces on the topographic surface. If you have a good match, the red plane will look like it penetrates the terrain along a single stratigraphic horizon. The plane will fit best nearest to the yellow placemark. Below, write the dip value that best fits the rock layers at Site 1.

Dip amount and direction at Site 1:

Double-click on the Site 2 placemark to take you to a bird's eye view of the site. Tilt and rotate until you have a view that looks obliquely NW along the line of flatirons toward Site 2.

Dip amount and direction at Site 2:

Zoom out a little, and fly around to see what you have constructed. The layers at Sites 1 and 2 clearly have very different dip directions. What happens between Site 1 and Site 2?

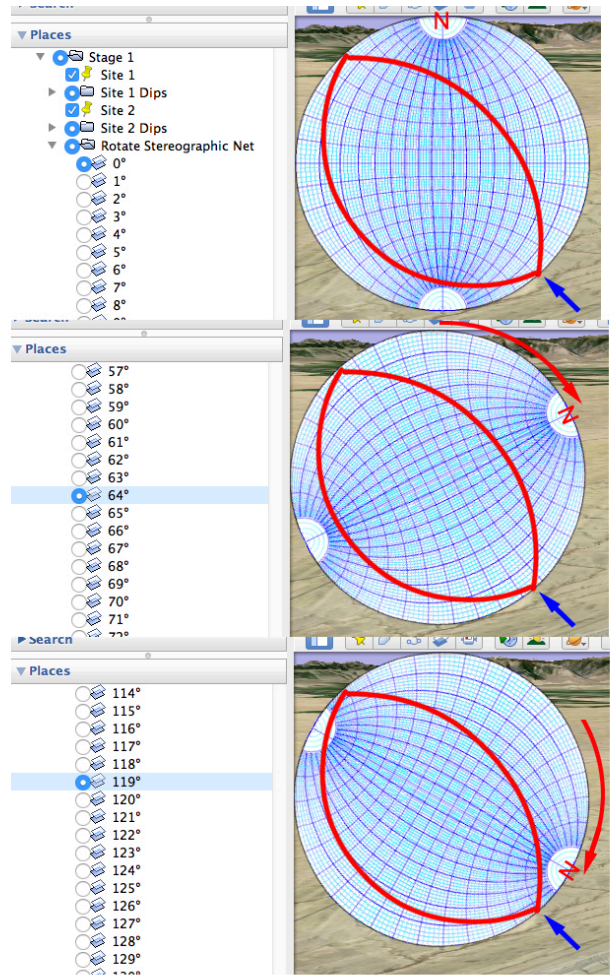
In the space below, sketch a schematic cross section from A to A'.

Now go back to Google Earth. What does the fact that the great circles for your two planes intersect in a horizontal line tell you?

If you haven't already done so, compress the dip value folders by clicking on the down arrows.

Finding the Trend of the Fold Axis. In the previous section, you should have reasoned out that the fact that the two great circles intersect in a horizontal line means that the **fold axis** calculated from these two dip values is **horizontal** (i.e., has a plunge of 0°). To completely specify the fold axis orientation, though, we also need the fold axis trend. If you were doing this by hand using a stereonet, you would determine the trend of the fold axis by reading the azimuth at the blue arrow (right).

- What you will do in this Google Earth application is find this azimuth by determining how many degrees you have to rotate the net to bring the north pole of the net to match the azimuth where the two planes intersect. The diagrams at right show two rotation steps (64° and 119°).
- Rotate N to match the fold hinge azimuth, and write the fold plunge and trend (properly recorded) below.

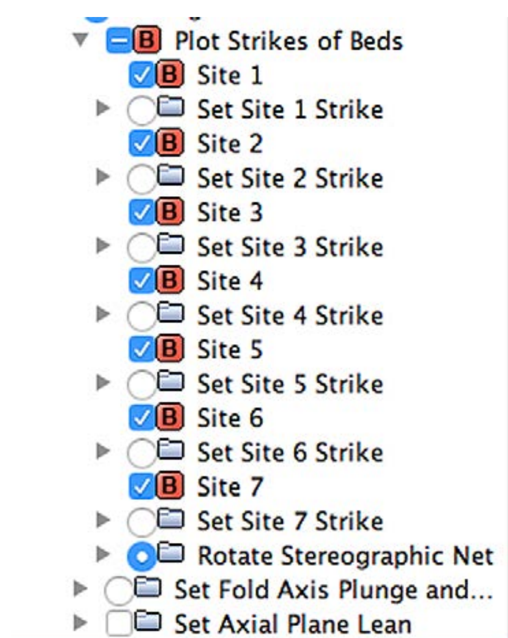


Compress the **Rotate Stereographic Net** folder by clicking the arrowhead, and then compress the Stage 1 folder.

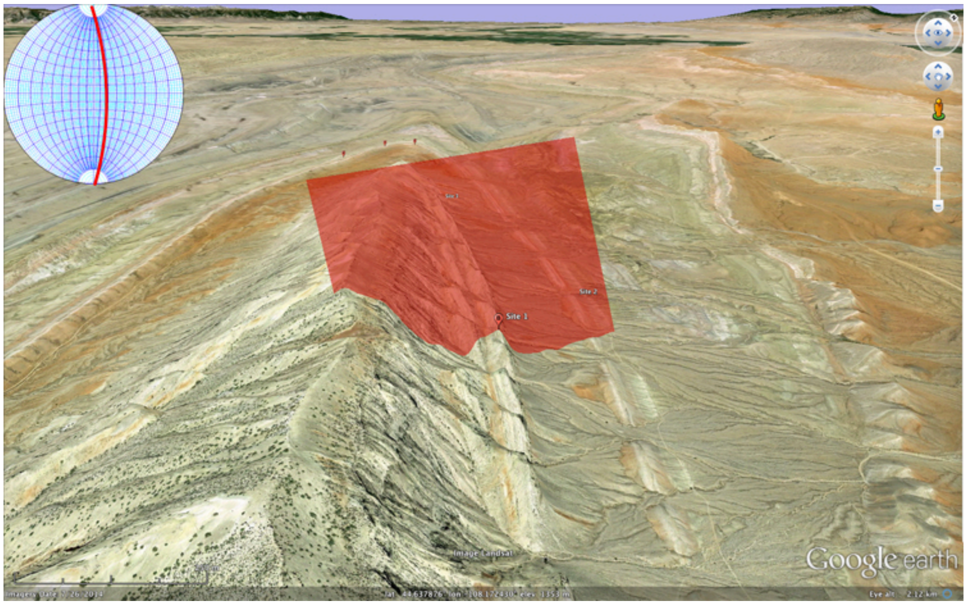
STAGE 2

Your next task will be to determine the orientation of sedimentary layers at the NW nose of the Sheep Mountain structure.

- Double-click on the Stage 2 folder to navigate to a bird's eye view of the Stage 2 area.
- Expand the **Stage 2** folder, and the **Plot Strike of Beds** folder. Highlight the radio button **for each of the sites** but **NOT** for the "Set .. Strike" folders (see right). Also highlight the **Rotate Stereographic Net** folder.
- Take a few minutes to fly through the region, and study the context of each of sites.



- Zoom vertically in to Site 1, and highlight the radio button for **Set Site 1 Strike**. Zoom and fly until you have the view shown in the image below.



Expand the **Site 1 Strike** folder, and you'll see a series of numbers. Choose one of the values by highlighting its radio button. Try choosing several more. What happens to the translucent red plane in the image as you choose different values?

Now, choose a number of different values, but watch closely what happens to the stereographic projection. You'll see that the ***dip*** remains the same but the **strike** changes (i.e., the curvature of the great circle remains the same, but the intersection of the great circle with the periphery changes as the strike changes). Try a plane with a strike of 137°, and then try a plane with a strike of 317°. Go back and forth between the two values. What happens to the plane in the imagery, and what happens to the great circle on the stereonet?

In contrast to the set-up for Stage 1, Stage 2 is designed to allow you to change the **strike** of the red plane, while holding the **dip** constant. The two values that you explored (317 and 137) are 180° apart. Remember that we report the orientation of a plane using the right hand rule, where the dip direction is clockwise (to the right of) the strike azimuth. So a plane with an orientation of 137, 50 dips to the SW, whereas a plane with an orientation of 317, 50 dips to the NE.

Your job now is to find the strike value that rotates each red plane until it best matches the strike of the layers in Google Earth. As in Stage 1, you will need to examine the clues presented by the various bedding traces on the topographic surface. If you have a good match, the red plane will look like it penetrates the terrain along a single stratigraphic horizon. The plane will fit best nearest to the yellow placemark. Below, write the strike value that best fits the rock layers at Site 1. Repeat for the other sites in the Stage 2 folder, turning each on in the side bar as you come to it. Record strikes below.

Strike at Site 1:

Strike at Site 2:

Strike at Site 3:

Strike at Site 4:

Strike at Site 5:

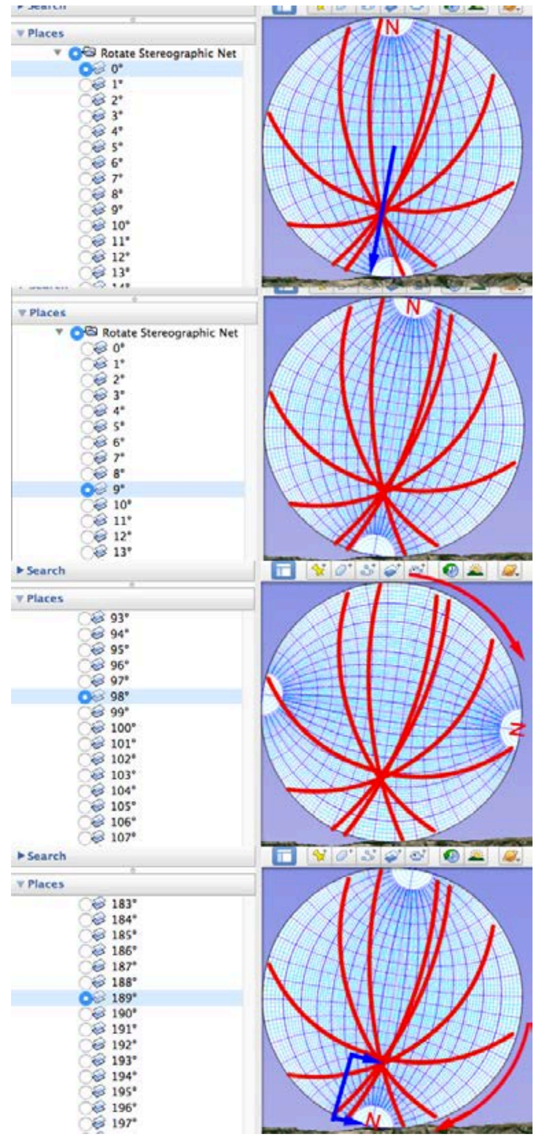
Strike at Site 6:

Strike at Site 7:

As you adjust the strike of bedding at each site, the great circles on the stereonet in the upper left corner change to reflect your estimates. If you have done a good job matching the strikes, the great circles will all intersect on the stereographic projection in approximately the same place. What is the significance of the orientation of the line represented in stereographic projection by the point where all of the great circles intersect? Why don't the great circles intersect at the periphery as they did for the portion of the fold in Stage 1?

In the space below, sketch a schematic cross section from B to B'.

Find the Trend of the Fold Axis by Rotating the Stereographic Net. In the previous section, you should have reasoned out that this portion of the fold is plunging, rather than horizontal, and the point where the great circles intersect will give you the plunge and trend of the fold axis for this portion of the fold. Because the plunge of the line of intersection is not 0° (as it was for the portion of the fold in Stage 1), you will need to determine both the trend *and* the plunge. If you were doing this by hand using a stereonet, you would determine the trend of the fold axis by reading the azimuth at the blue arrow (above right – note! The example in the picture is ***different*** from the one you are working on, so don't panic when yours doesn't match this figure!). As you did before, you will find the azimuth by determining how many degrees you have to rotate the net to bring the North pole of the net to match the azimuth of the line of intersection. The diagrams at right show three rotation steps (9°, 98°, and 189°). A rotation of 189° brings North on the net into line with the fold azimuth, so 189° is the fold trend.

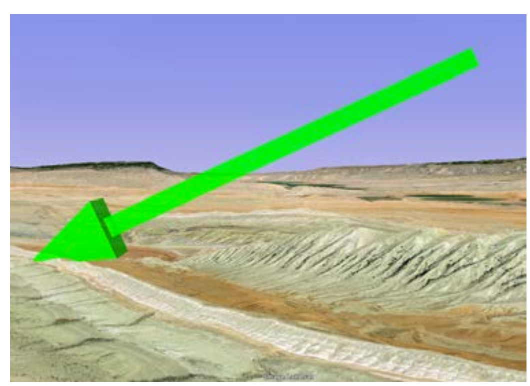


To determine the fold plunge, we need to count the number of degrees in from the perimeter of the net along the azimuth direction (shown by the blue bracket in the image bottom right). For the example at right, the plunge is about 35 ° (again, this is different from yours).

OK! Back to your own fold data. Expand the folder **Rotate Stereographic Net** for Stage 2. Rotate N to match the fold hinge azimuth, estimate the plunge, and write the fold plunge and trend (properly recorded) below.

Find the Fold Axis Plunge and Trend using the Green Arrow.
You're now going to add a 3D arrow representing the fold axis.

- Expand the **Set Fold Axis Plunge and Trend** folder.
- Expand the various plunge folders; experiment with different combinations of plunge and trend. Be sure to tilt the image in Google Earth and see what changing the fold plunge and trend does to the green arrow.



Now, go back to the previous section, and get the fold plunge and trend that you determined from the stereonet, and select a value close to your determined value from the options in the sidebar. Fly around the fold. Does the green fold axis arrow that you've chosen make sense for the strikes and dips of bedding that you estimated using the red planes? Explain.

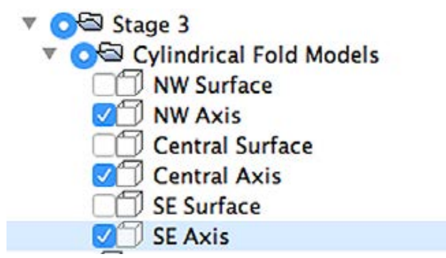
Set the Axial Plane. The fold axis and axial plane of a fold are not independent – the fold axis is a line within the axial plane. Start by rotating your view until you are looking directly down the green fold axis arrow from the previous section. Be sure that your red planes are still turned on from the first part of Stage 2.

Highlight the radio button for the folder **Set Axial Plane Lean**. Choose the 9 o'clock option, and a teal-colored plane will appear. Is this a good candidate for the fold axial plane? Why or why not?

Experiment with the other possible orientations for the axial plane. Which is the best fit option? Justify your choice, and be sure to include what you know about the dips of bedding!

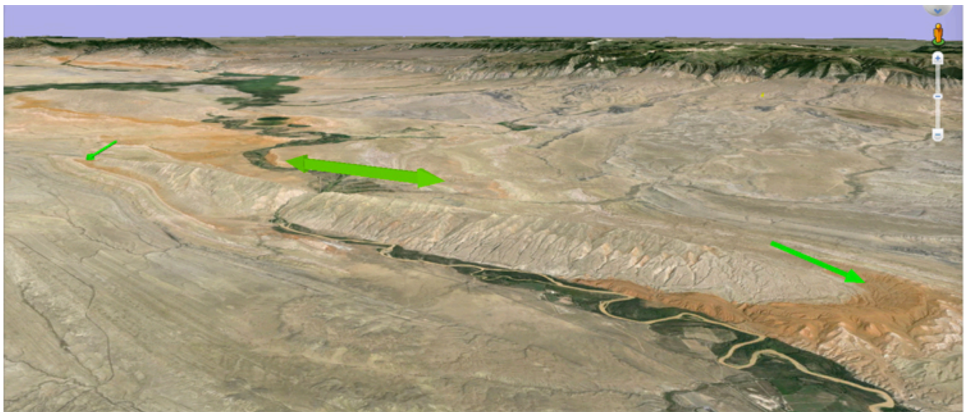
Once you have a reasonable orientation for the axial plane of your fold, add the trace of the axial plane to your B-B' cross section.

STAGE 3



Your next task will be to explore the overall geometry of the entire Sheep Mountain Anticline.

- Double-click the **Stage 3** folder, and expand the **Cylindrical Fold Models** folder. Turn on **only** the NW Axis, Central Axis, and SE Axis. Leave the other items turned off.
- Zoom in, tilt and fly around the area, and compare the three fold axes shown with the green arrows. The Central and NW fold axes are located where you worked on Stages 1 and 2 respectively (the center and left arrows in the image below).



Estimate the trend of the SE Axis in a vertical view looking directly down on the green arrow in Google Earth. Remember that trend is always measured in the direction of plunge. Estimate the plunge from a low angle view looking perpendicular to the green arrow. What is the approximate plunge and trend of the SE Axis, and how does this compare to the orientation of the other two axes?

In the space below, sketch a schematic cross section from C to C' across the SE end of the fold.

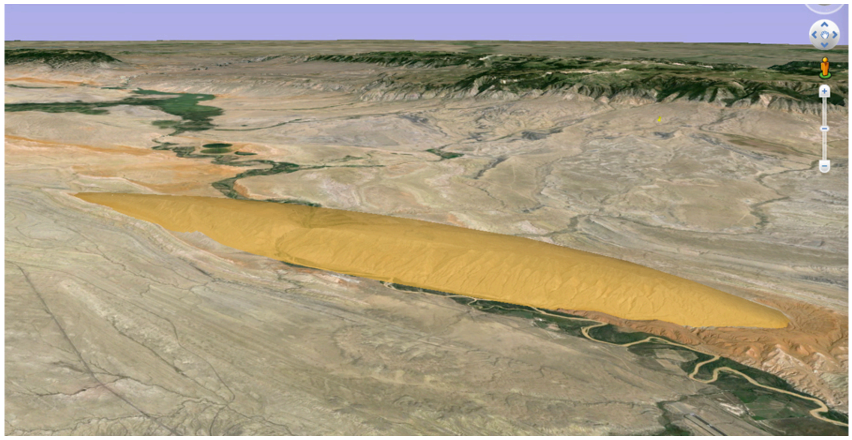
Is the Sheep Mountain Anticline a cylindrical fold or not? Explain, describe its geometry, and account for the fact that all three of your cross section sketches (A-A', B-B', and C-C') look similar.

In the space below, sketch a schematic cross from D-D' along the length of the Sheep Mountain Anticline.

Aside from being more elongate, why does cross section D-D' (which lies along the structure) look broadly similar to your other three cross sections (which lie across the structure)?

The Sheep Mountain Anticline is a doubly plunging fold, also known as a *periclinal* fold. The Sheep Mountain Anticline can also be described as a *whaleback* anticline because it looks like the back of a whale arching out of the water.

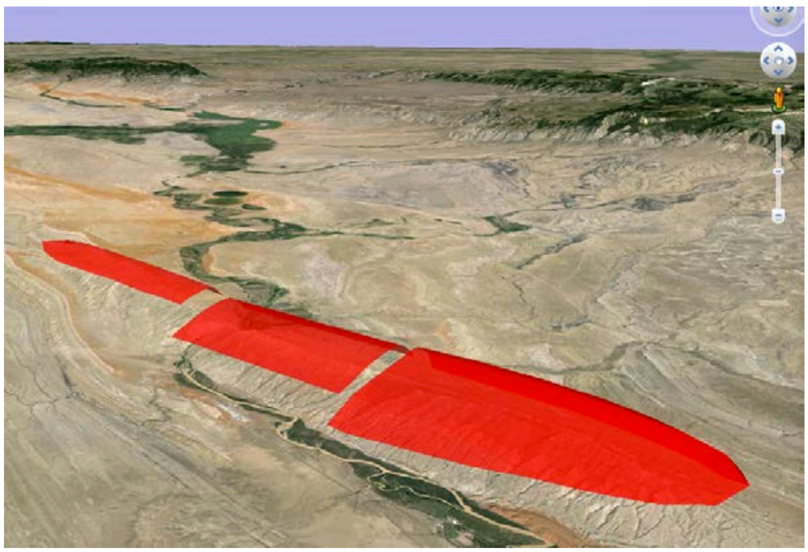
Now turn on the **NW, Central, and SE Surfaces**, also leaving the fold axes turned on and all other items off. These red surfaces represent an approximation of the shape of the folded layers. Each is *locally* cylindrical – in fact, in order to calculate a fold axis for each of the areas in Stages 1 and 2 using the stereonet, we had to assume that each small portion of the fold is, in fact, cylindrical, even though the entire fold structure is clearly not. Tilt and fly around the area to admire the geometry.



Now, turn **off** the Cylindrical Fold Models folder and turn **on** the **Generalized Model**. This mustard-colored surface is a general approximation of one of the bedding surfaces of the Sheep Mountain Anticline.

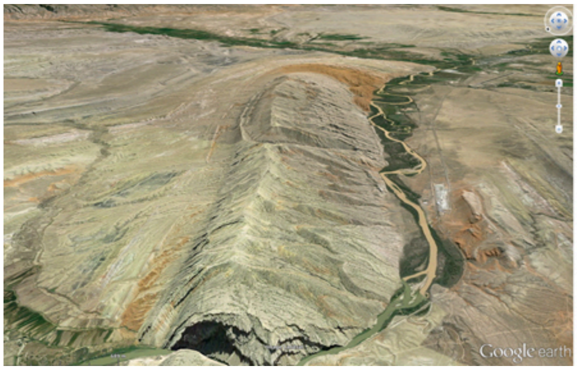
Zoom in, tilt, and fly around. You'll see that the surface is only a general approximation, because the actual fold geometry is more complex than this simplified rendition.

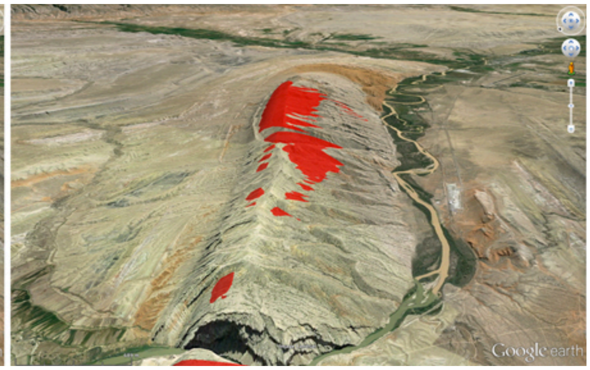
Turn off the Generalized model. Highlight the **1000** radio button, and zoom in to an oblique view approximately like the one below.

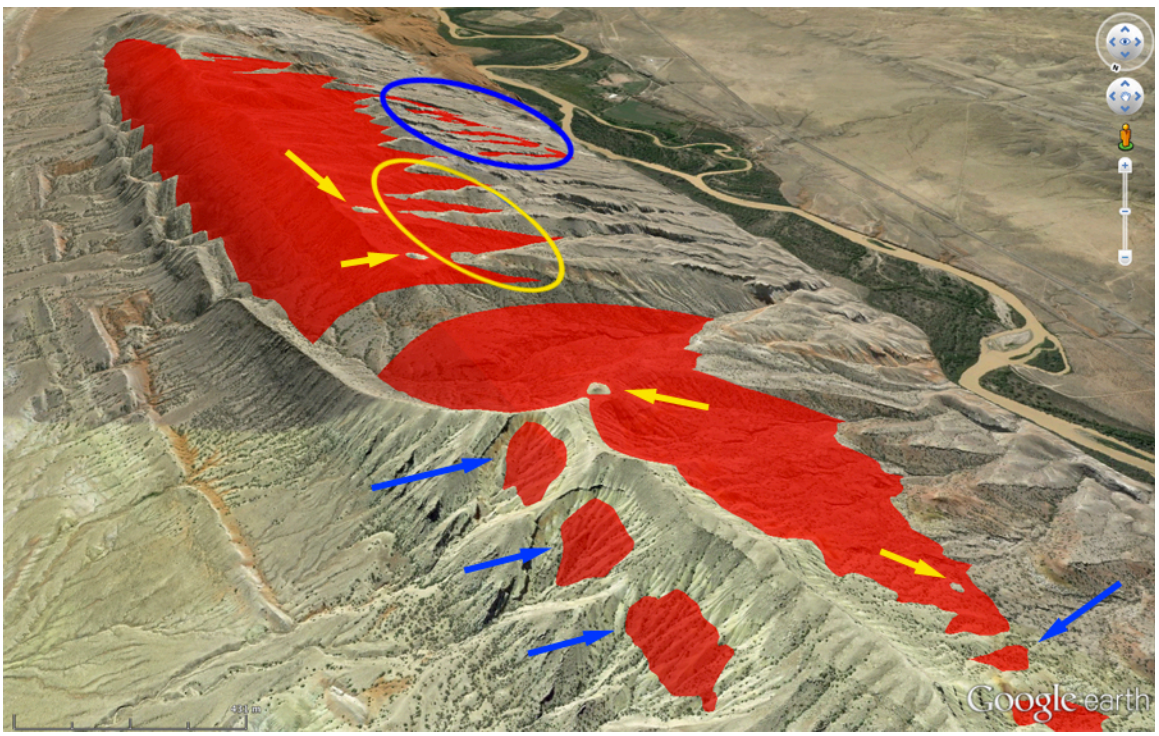


- Click radio buttons with selectively smaller numbers, and observe what happens in the image.
- Each red surface is an approximation of the shape and location of a bedding surface at a successively lower stratigraphic level.
- At 1000, the bedding surface is entirely above ground (and therefore eroded away) except where it would project into the ground on the flanks of the fold.
- As you pick lower and lower horizons, you'll see parts of the red layer disappear below ground level.
- At 300, the red surface is entirely stratigraphically below ground level.

Fly to an oblique view approximately like the one below left, and start with the 300 surface selected. Select selectively higher surfaces, and observe the patterns created by the intersection of an individual bedding surface with the topography of Sheep Mountain (below right). Be sure to fly around, zoom in, and view each from more than one vantage point.





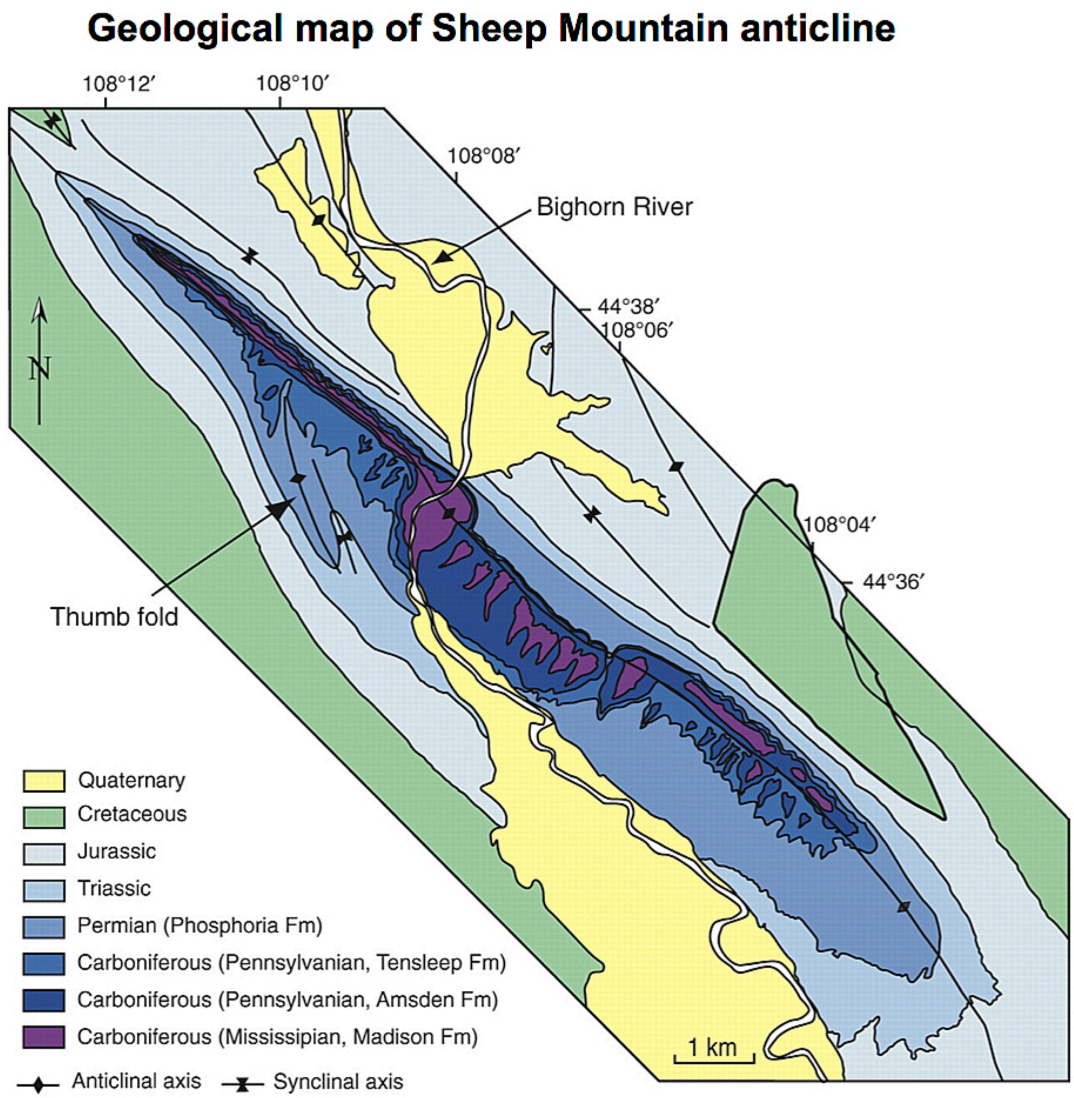


The image above shows a view of the 475 surface. Colored arrows show “patches”, and the colored ovals show “fingers”.

What accounts for the red patches shown by the blue arrows, and what accounts for the gray-tan patches shown by the yellow arrows?

What accounts for the red fingers outlined by the blue oval, and what accounts for the gray-tan fingers outlined by the yellow oval?

Below, you'll see a published geologic map of the Sheep Mountain Anticline, and you'll see that the geologic map also has patches and fingers. Annotate the geologic map, and indicate which parts of the geologic map are analogous to each of the following from the previous question: the red patches, the gray-tan patches, the red fingers, and the gray-tan fingers. Justify your choices.

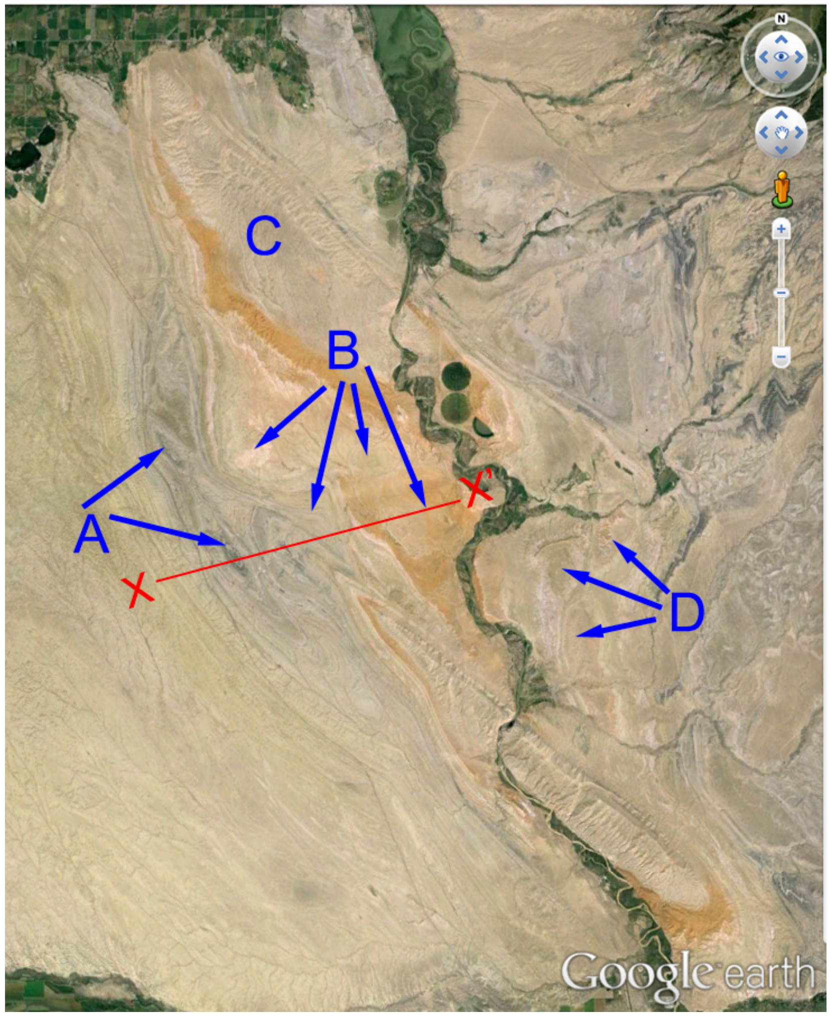


Patricia Fiore Allwardt et al. Geosphere 2007;3:408-421

In Google Earth, go to a vertical view with N at the top, which is the same bird's-eye view shown in the geologic map. Try out a number of the red surfaces to find the one that most closely matches the geologic map in terms of map pattern. Which surface did you select, and why?

Applying what you have learned

Sheep Mountain is not the only fold in this area. Zoom out to a vertical view that shows roughly the same area as shown in the image at right.



In Google Earth, zoom in and examine the folds shown by the arrows. Are all of them anticlines, or are some of them synclines? How can you tell?

Add an "A" to the image at right for each anticline and an "S" for each syncline.

Are all of the folds periclinal? Explain.

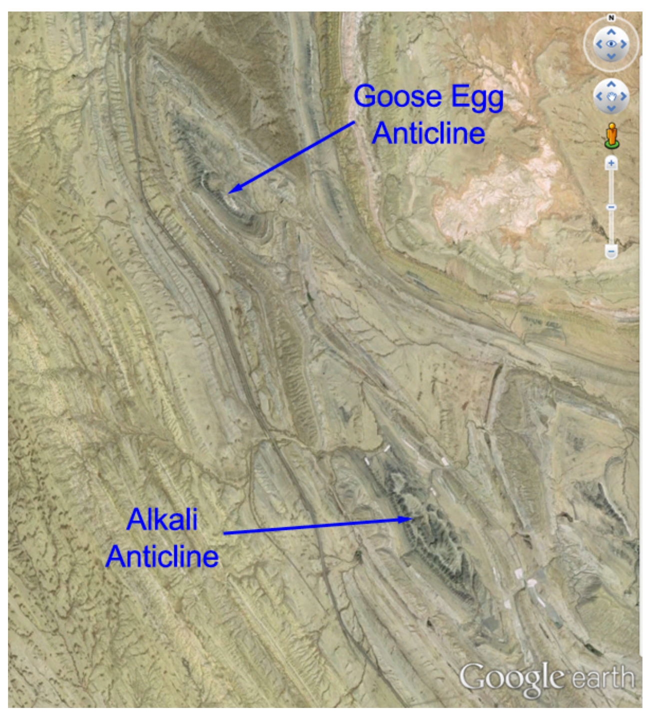
Some of the periclinal folds are fairly equidimensional and are better termed structural basins (if synclinal) or structural domes (if anticlinal).

In the space below, sketch a schematic cross section from X to X'.

Earlier in this exercise, we described the Sheep Mountain Anticline as a whaleback anticline. One of the places in the world that has many spectacular whaleback anticlines is the Zagros Mountains of Iran. Fly to 28.090556, 53.799540 and an eye altitude of about 400 km (view below). Zoom out a bit so that you can see where you are in the world, then zoom back in to an eye altitude of about 400 km.

All of the giant slugs in the view are whaleback anticlines. Zoom in, tilt, and fly around, and explore these fabulous whalebacks. Are they indeed anticlines? How do you know? And are they doubly plunging? How do you know?

Go back to the Sheep Mountain area, and fly to 44.687949, -108.273338 and an eye altitude of about 12 km. You'll see the two anticlinal structures (Goose Egg Anticline and Alkali Anticline, labeled at right) that lie just NW of the Sheep Mountain Anticline. Earlier in this section, you should have determined that these are both doubly plunging (periclinal) anticlines. Zoom in, tilt, and fly around these anticlines. As you've seen at Sheep Mountain and in the Zagros, whaleback anticlines are highest topographically in the middle of the anticline, like a giant whale's back. Are the Alkali and Goose Egg anticlines also *whaleback* anticlines, or have the anticlinal cores been eroded?



This is a good lesson to learn! Not all anticlines are topographic highs – the cores of many anticlines sit topographically lower than the resistant units that define the limbs. Such anticlines are commonly referred to as *breached* anticlines.

This area of Wyoming is part of the Bighorn Basin Oil and Gas Province. Fly to 44.706209, -108.296247 in the Goose Egg Anticline, and zoom to an eye elevation of about 1.5 km. You'll see a set of tanks and evidence of other activity associated with petroleum extraction. In the main menu bar, click on the clock icon to bring up historical imagery, and select the 2011 imagery. The sun angle is a little different in this imagery, and you can actually see the shadow of a pump jack!! Does it surprise you that they have drilled the core of an anticline and found petroleum? Explain.

Turn off the historical imagery by clicking again on the clock icon. Fly to 44.680737, -108.183961, and zoom to an eye altitude of about 3.0 km. You'll see more evidence of oil wells. Zoom out a little. This is one of the folds that you looked at earlier. Have they drilled a structural dome or a structural basin here? Does this make sense?

Wrap-up

Now that you've finished the Fold Analysis Challenge, what "Ah-ha" insights did you have with respect to folds, fold geometries, analyzing folds, and visualizing folds? An Ah ha! insight is a leap in insight about a particular topic – suddenly a whole bunch of things come together, the murkiness clears, and you realize that your understanding of (or view on) a particular topic or concept has just taken a huge leap. It's not simply a description of what you learned about. One way to write an Ah ha" insight is to say, "I used to think that X and now I realize that Y because…"