Student Name: ______________________________ Grade: ____

Physical Geology 101 Laboratory

Identifying Geologic Deformational Structures and the Crustal Forces that Create Them

Purpose and Learning Objectives: Structural geology is the study of how geologic rock formations are spatially arranged, stressed, and deformed into structures such as folds and faulted blocks. Spatial relations between and within rock formations can change when excessive crustal stresses (forces) cause rocks to strain (deform), typically during mountain-building events. Structural geology focuses on understanding the dynamic tectonic conditions and timing of deformation events and resultant deformation structures.

The **purpose** of this lab is to become successful at applying the principles of structural geology for both, interpreting surface and subsurface structural and geologic relations, stress and strain regimes, and solving structural problems, concerning geographic regions that expose a rock record of igneous, metamorphic, and sedimentary events, folding and faulting, and surface erosion.

The terms and concepts of geologic structures, the application of structural geology to mountain building events, and the techniques used to interpret geologic structures will be explored in this lab. You will be analyzing, measuring, and identifying deformational rock structures by examining three types of graphic representations of geologic structures: 1) geologic maps, 2) geologic cross sections, and 3) block diagrams, along with ground and aerial images.

<u>The learning objectives for this lab are as follows:</u>

- Become familiar with structural terminology and spatial concepts of attitude, strike, dip direction, dip angle, faults, folds, and geologic block diagrams, maps and cross sections.
- Recognize and understand the geologic map symbols for dipping strata, vertical strata, horizontal strata, non-plunging and plunging anticlines, non-plunging and plunging synclines, normal and reverse faults, left- and right-lateral strike-slip faults.
- Recognize geologic structures on block diagrams, including geologic maps and cross-sections, based on rock formation patterns and map symbols.
- Interpret the geologic history of an area based on the information on a geologic maps, cross-sections, and ground and aerial images.

Lab Activity Overview: This lab's activities have five parts:

Part I – is a preview of important terms and concepts used in structural geology.

Part II - is an activity designed to learn about the basic types of faults, their unique features, measuring, Interpreting, and identifying their structure and the stresses that cause them to form and displace.

Part III - is an activity designed to learn about the basic types of folds, their unique features, measuring, interpreting, identifying their structure and the tectonic stresses that cause them to develop.

Part IV – is an activity designed to apply your newly gained knowledge of faults and folds towards identifying, measuring, and interpreting folds and faults on maps, cross-sections, and block diagrams..

Lab Activity Preparation and Resources: Please pay special interest to the lab manual chapter, my lab PowerPoint slides, and the lab worksheet figures – that is where you will find most of the needed information to help you complete this worksheet. However, I have compiled a very substantial set of online publications and videos that will provide you with very helpful background information on the different aspects of structural geology. Please study these sources for preparation and while completing the worksheet for this structural geology virtual lab. If you are having trouble on a certain section, and need additional guidance and/or information, check the list below for the appropriate topic information, and of course, contact me for help and guidance too.

Lab Manual Chapter Covering Structural Geology:

Lab Manual Structure Chap: http://www.geoscirocks.com/Geol101_Lab_Manual_Ch12_Crustal_Deformation_Structural_Geology.pdf

PART I. STRUCTURAL GEOLOGY BASICS: Structural Terms and Determining Attitude of Structures

Major Types of Geologic Structures and Terms

A body of rock that has a unique age, lithology, and is big enough to be drawn on a map, is called a ***formation***. The interface or boundary that separates two rock formations is called a ***contact***. Places on Earth's surface where rock formations are exposed (not covered by sediment and vegetation) are called ***outcrops***. Rock formations consisting of undisturbed strata - sedimentary beds and lava flows - are typically horizontal and planar in spatial orientation. However, shifting tectonic plates produce **directed stresses** in the crust that will, over time, cause **crustal strain or deformation** in strata, which imparts a change in the rock body's shape and/or attitude, such as tilting, faulting, and folding. Horizontally-directed tectonic stresses include **tension** (pull apart), **compression** (push together), and **shear** (push past).

There are a number of deformed structures that result from directed crustal stresses. **Joints** are planar fractures in rock caused by stress where there is no rock offset along the fractures. **Faults** are also stress-induced planar fractures in the crust where rock gets offset along those fractures. **Folds** are regions of compressed crust where strata become tilted and buckled (shortened and thickened). Faults and folds that are exposed at the earth's surface have unique structural characteristics – spatial formation patterns and attitudes - that can be observed, mapped, identified, categorized, and analyzed.

Carefully study the major structural features listed and described in your lab manual and in lab PowerPoint and the additional lab worksheet references listed above. You will get to explore these structures in greater depth in Parts II, III, and IV. See **Figures 1** through **7** for examples of the above terms. Very good sources of information on the introduction to structural geology are found in the following URL's:

1- Basics of Geologic Structures: https://academic.csc.edu/mleite/wvc/Basics/structures.html

2 - Geologic Structures1: https://www.youtube.com/watch?v=oflkpZCKDy0

3 – Geo-Structures: https://courses.lumenlearning.com/wmopen-geology/chapter/outcome-geologic-structures-from-deformation/

4 - Tectonic Structures: http://profharwood.x10host.com/GEOG102/Study/tecton1.htm

5 – Glossary of Structure Terms: https://openeducationalberta.ca/introductorystructuralgeology/back-matter/942/

Figure 1 – Examples of an Outcrop – Ayers Rock, AUS

Vasquez Rocks, CA

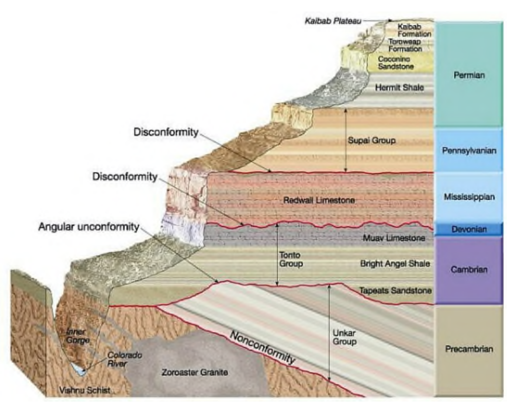


Figure 3 – Image of Grand Canyon and Cross-Section of Rock Formation of the Grand Canyon

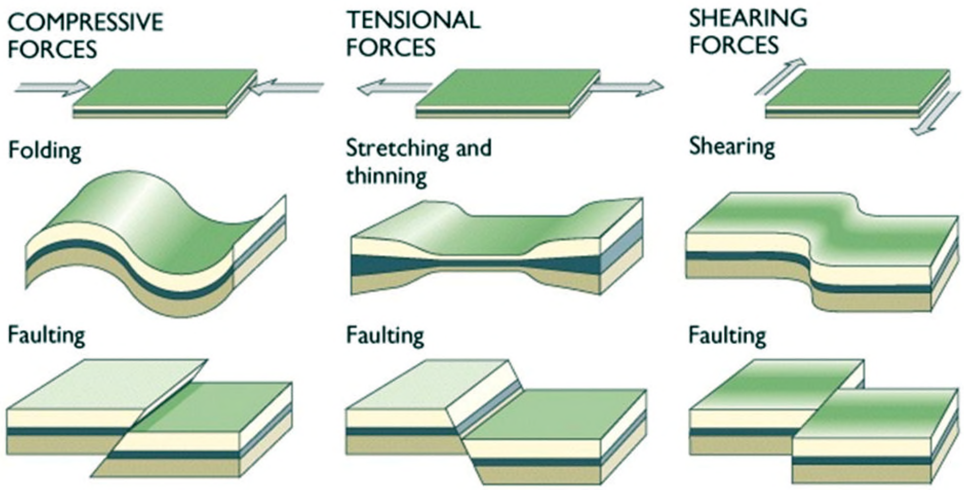


Figure 4 – Three Types of Directed Crustal Stresses

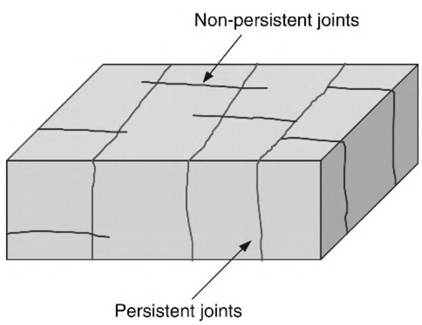


Figure 5 – Rock Joints

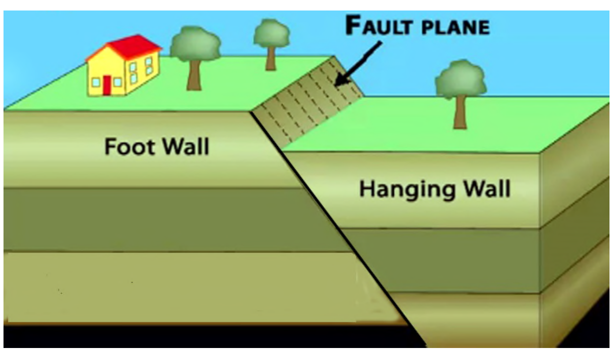


Figure 6 – Geologic Faults

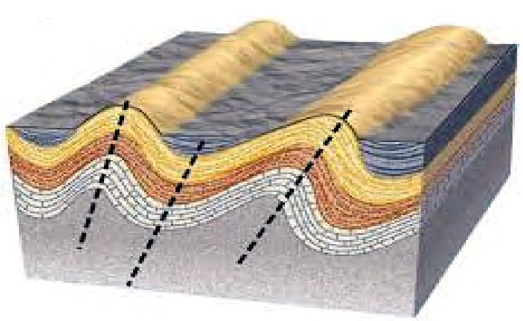


Figure 7 – Geologic Folds

1) Important Structural Terms – Briefly define these general geologic structural terms below:
URL to a glossary of structural geology terms: http://www.geoscirocks.com/glossary_structural_terms.pdf

Outcrop - ____

Formation - ____

Contact - ____

Tensional stress - ____

Compressional stress - ____

Shear stress - ____

Strain - ____

Joint - ____

Fault - ____

Fold - ____

Geologic Structure Illustrations: Geologists depict or model geologic structures of the Earth's crust by using block diagrams, maps, and cross section illustrations to analyze and decipher the structures in three different dimensions. Illustrations that have a 3-D view = top plus sides are called ***block diagrams or 3D models;*** Illustrations that only show the horizontal/top view are called ***map views or geology maps***. And finally, illustrations that only show the vertical/sides view are called (geologic) ***cross-sections***. See **Figures 8, 9, 10** for examples.

Geologic structural illustrations are very helpful for understanding the various types of geologic structures in the Earth's crust, and for studying Earth's geologic history. Note that you have already studied topographic maps, which are "map view" illustrations of earth's geographic surface. And you have also studied stratigraphic cross-sections for geologic dating purposes, which are basically geologic cross-sections. In this lab activity, you will be using all three types of illustrations to learn about the attitude of structures, including strike and dip, faults and folds. Understandably, mastering the basics of structural geology is quite difficult because, it requires the student to learn a large number of new geology terms and concepts that are based on three-dimensional reasoning and visualization.

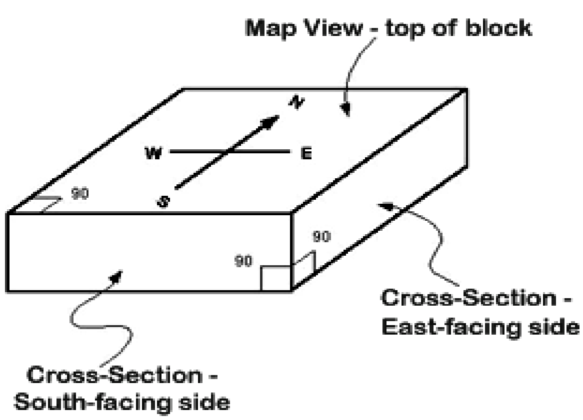


Figure 8 – Three-Sides of a Block Diagram

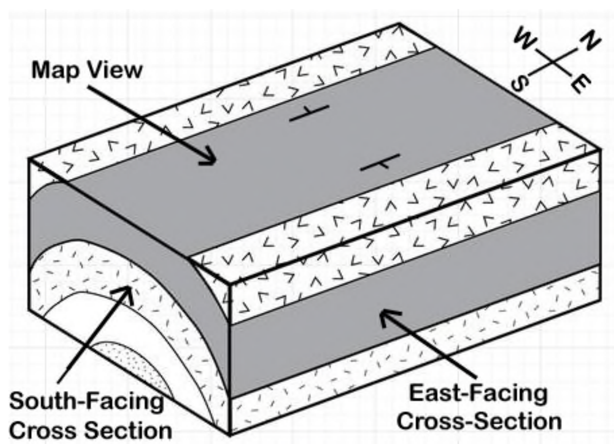


Figure 9 – Geologic Block Diagram with a Fold

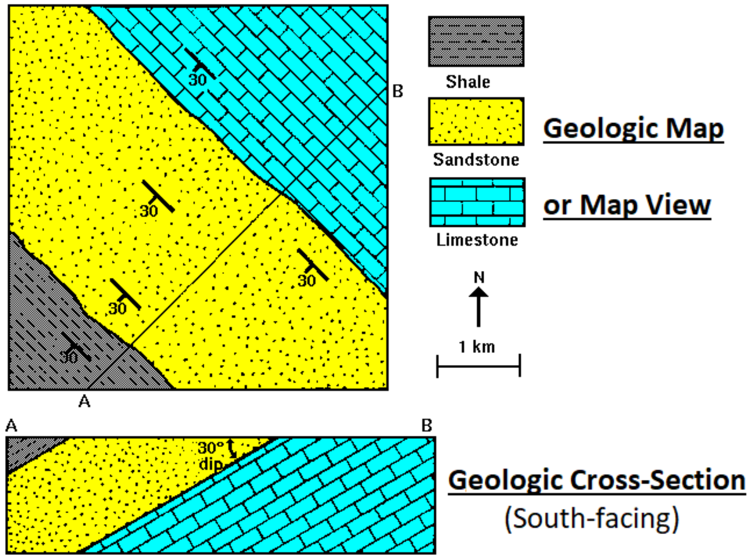


Figure 10 – A Map View (geology map) with a (geologic) Cross-Section

2) Important Structural Terms – Briefly define these general geologic structural terms below:

Block Diagram - ____

Map View ____

Cross-section - ____

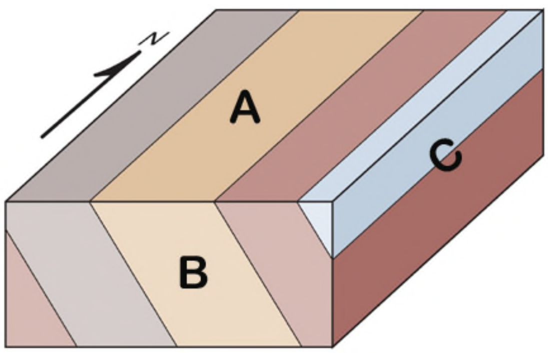


Figure 11 – Block Diagram for Labeling Exercise

3) Properly label the three faces of this block diagram to the right in **Figure 11**. Use terms in **Figures 9 and 10** above to correctly describe/label the three faces.

Face A = ____________________________

Face B = ____________________________

Face C = ____________________________

4) Which side(s) of the block diagram would a topographic map or geology map be on?

5) Which side(s) of the block diagram would a stratigraphic column – like the geological dating lab figures- be on?

<u>Measuring the Attitude of Geologic Structures – Lines, Planes, Directions, and Angles:</u>

The term, "***attitude***" is used for the orientation of planar-form rock structures in three-dimensional space, like strata bedding or a fault surface. Two aspects of attitude are needed to define a planar feature's orientation in 3-D space: 1) ***Strike*** and 2) ***Dip.*** For the rest of this lab activity, you will determine/use strike and dip to describe the orientations of structures in block diagrams, maps, and cross-sections. Use the URL's below to help you understand what strike and dip are, and how to master determining strike and dip – on block diagrams, maps, cross-sections, and out in the field:

1 - Bedding Attitude: https://fog.ccsf.edu/~kwiese/content/Classes/Attitudes/Attitudes.html

2- Strike and Dip: https://openpress.usask.ca/geolmanual/chapter/overview-of-strike-dip-and-structural-cross-sections/

Strike is a horizontal line formed by the intersection of a horizontal plane and the (inclined) plane of the rock feature. Strike is a horizontal linear map direction or bearing measured with a compass as either an azimuth or a quadrant value – just like you did with a direction from one location to another on a topographic map. The strike's compass direction is the angle that the strike line makes with respect to north. In the figure below, the strike of the inclined plane is 45 degrees west of north, so the angle between the strike line and north is 45°. Thus, the strike of the inclined plane would be "north forty-five degrees west", which you can write as, "N45W". Note that N45W is in quadrant notation, and that the same direction in azimuth notation is 315 - they are equivalent—they communicate the same thing.

Dip is the angle between the horizontal plane and the (inclined) planar rock unit or feature. Dip direction is always in the downward-sloped direction of the inclined plane and is always perpendicular to the strike. The "dip" of a planar feature includes two components: 1) dip angle, and 2) dip direction. Dip angle can be described as either low-angle (Less than 30°), medium-angle (30° to 60°) or high-angle (greater than 60°)

You measure the dip angle with an inclinometer – it's like a protractor. You measure dip direction with a compass – like strike. Note that dip is always perpendicular to strike, so you dip direction is always 90° off from the strike – either to the west or to the east. Thus, the dip is described as an angle (in degrees) with a direction (cardinal direction). The strike and dip of an inclined planar feature is recorded with strike first followed by dip. For example, the strike and dip for **Figure 13** is N45W 20SW. Another example of strike and dip is in **Figure 14**, which is N-S 30E.

The strike and dip concept is important in structural geology, and represents a handy way to describe the 3-dimensional orientation of planar geologic structures, including faults, tilted strata, fold limbs, and fold axes.

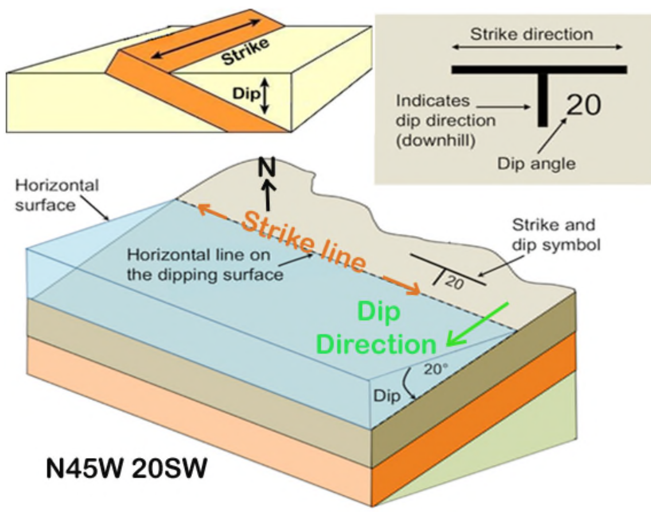


Figure 12 – Illustrations Showing the Attitude (Strike and Dip) of Tilted Strata

To re-summarize, if you want to describe the 3-dimensional orientation of a planar feature such as a fault, an axial plane of a fold, or dipping strata, you can do so using three components: strike (bearing direction), dip angle, and dip direction. Together, these three components are called "strike and dip", or simply, "attitude." Strike and dip are drawn on geologic maps as a "T-like" symbol – the long segment is the strike and the short segment the dip. A number next to the short segment of the symbol represents the dip angle. The notation for strike and dip is shown in **Figures 12 and 13.**

Geologists measure structural attitudes in the field with a field compass (for the strike) and an inclinometer (for the dip). Note that most field compasses come with a built-in inclinometer like a Brunton and Silva. See **Figure 13** below.

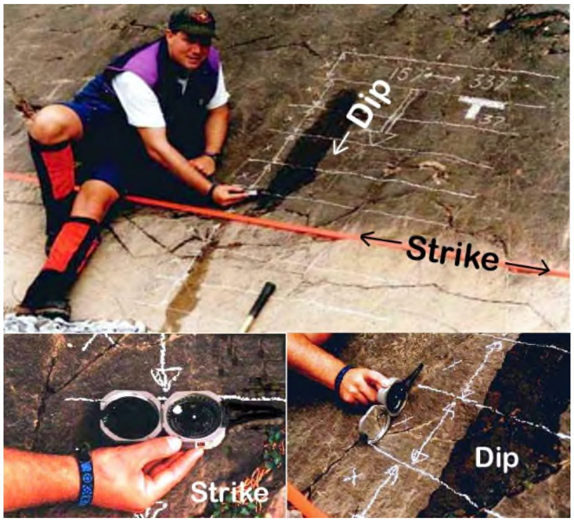


Figure 13 – Measuring Strike (w/compass) and Dip (w/inclinometer) in the Field

6) Important Structural Terms – Briefly define these three geologic structural terms below:

URL to a glossary of structural geology terms: http://www.geoscirocks.com/glossary_structural_terms.pdf

Attitude - ____

Strike - ____

Dip -____

Strike and Dip Rules for Interpreting Geologic Structures: There is a structural relationship between a set of tilted strata and their strike and dip. These relationships could be considered like rules or principles, like the stratigraphic principles that you learned in geologic dating. The first rule states that the strike of tilted beds is parallel to the adjacent contacts between the beds. Another rule is states that the dip direction of the tilted layers is towards the younger rock layers. The third rule states that the apparent width a rock layer cropping out at the earth's surface will vary depending on the dip angle of the layer – widest with lowest angle dip, and narrowest with highest angle dip These rules will become very helpful for completing Parts II-IV.

Rules of Srike and Dip

1) Strike of beds is always parallel to the direction of the contacts.

2) Rock layers dip towards the youngest exposed rock layers.

3) Steeper the dip of the layer, the narrower the width of its outcrop.

Below are two exercises that will help you learn how to interpret bed attitude using strike and dip.

Block Diagram Exercise #1

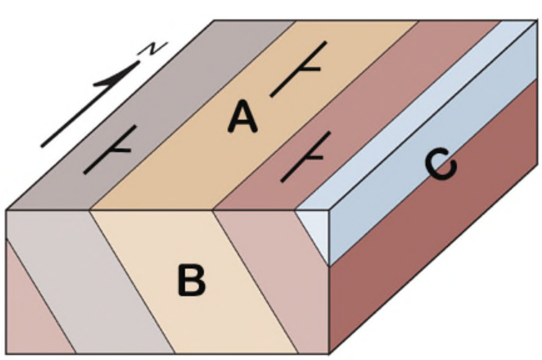


Figure 14 – Block Diagram for Strike and Dip Exercise #1

Study the strike, dip, bed thickness, and map-view age pattern of the tilted bed of rocks in the block diagram above in **Figure 14**. Note the north direction arrow for cardinal orientation. Answer the following questions:

7) What is the strike (direction or bearing) for the tilted beds in the above block diagram?

8) Is the strike (direction or bearing) for the tilted beds parallel to the adjacent contact lines?

9) Which direction do the tilted beds dip in the above block diagram?

10) Does the dip direction point towards the youngest or the oldest rocks in the block diagram?

11) What is dip angle (rough estimate) for the tilted beds dip in the above block diagram?

12) Is the width of the beds at the ground surface wider, narrower, or the same as true bed thickness?

13) Based on your answers above, do these tiled beds follow the strike and dip rules listed above?

14) Write the full notation for strike and dip for the tilted beds dip in the above block diagram?

Block Diagram Exercise #2

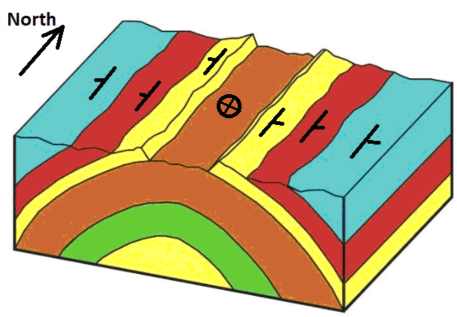


Figure 15 – Block Diagram for Strike and Dip Exercise #2

Study the strike, dip, bed thickness, and map-view age pattern of the tilted-folded bed of rocks in the block diagram above in **Figure 15**. Note the north direction arrow for cardinal orientation. Answer the following questions:

15) What is the strike (direction or bearing) for the tilted beds in the above block diagram?

16) Is the strike (direction or bearing) of the tilted beds parallel to the adjacent contact lines?

17) Which direction(s) do the tilted beds dip in the above block diagram?

18) Does the dip direction(s) point towards the youngest or the oldest rocks in the block diagram?

19) What is dip angle (rough estimate) for the tilted beds dip in the above block diagram?

20) Is the width of the beds at the ground surface wider, narrower, or the same as true bed thickness?

21) Based on your answers above, do the strike and dip rules make sense?

22) Write the full notation for strike and dip for the tilted beds on the WEST side above block diagram.

23) Write the full notation for strike and dip for the tilted beds on the EAST side above block diagram.

Geologic Map Symbols: Geologic symbols are used on geology maps and cross sections to indicate one or more structural characteristics of the rock formation at the point on the map that they (the symbols) are placed. Some commonly used map symbols are found in the **lab manual** (you will refer to these symbols for interpreting and making geologic maps, cross sections, and block diagrams). **Figure 16** shows many of the commonly-used map symbols. Map symbols indicate **1**) *attitude* (e.g. strike and dip of either, bedding or foliation), **2**) *formation contacts*, 3) *fault lines* (rock type, location, and planar orientation), **4**) *fold axes* (type, location, and their limb orientations), and **5**) rock formation information (type, name, and age). You will need to be able to recognize and interpret these symbols while working on geologic maps, cross sections and block diagrams found in Parts II, III, and IV of this lab. See the link below for more information on geologic map symbols:

https://academic.csc.edu/mleite/wvc/Basics/BscsTables/geomapsymb.html#foldstable

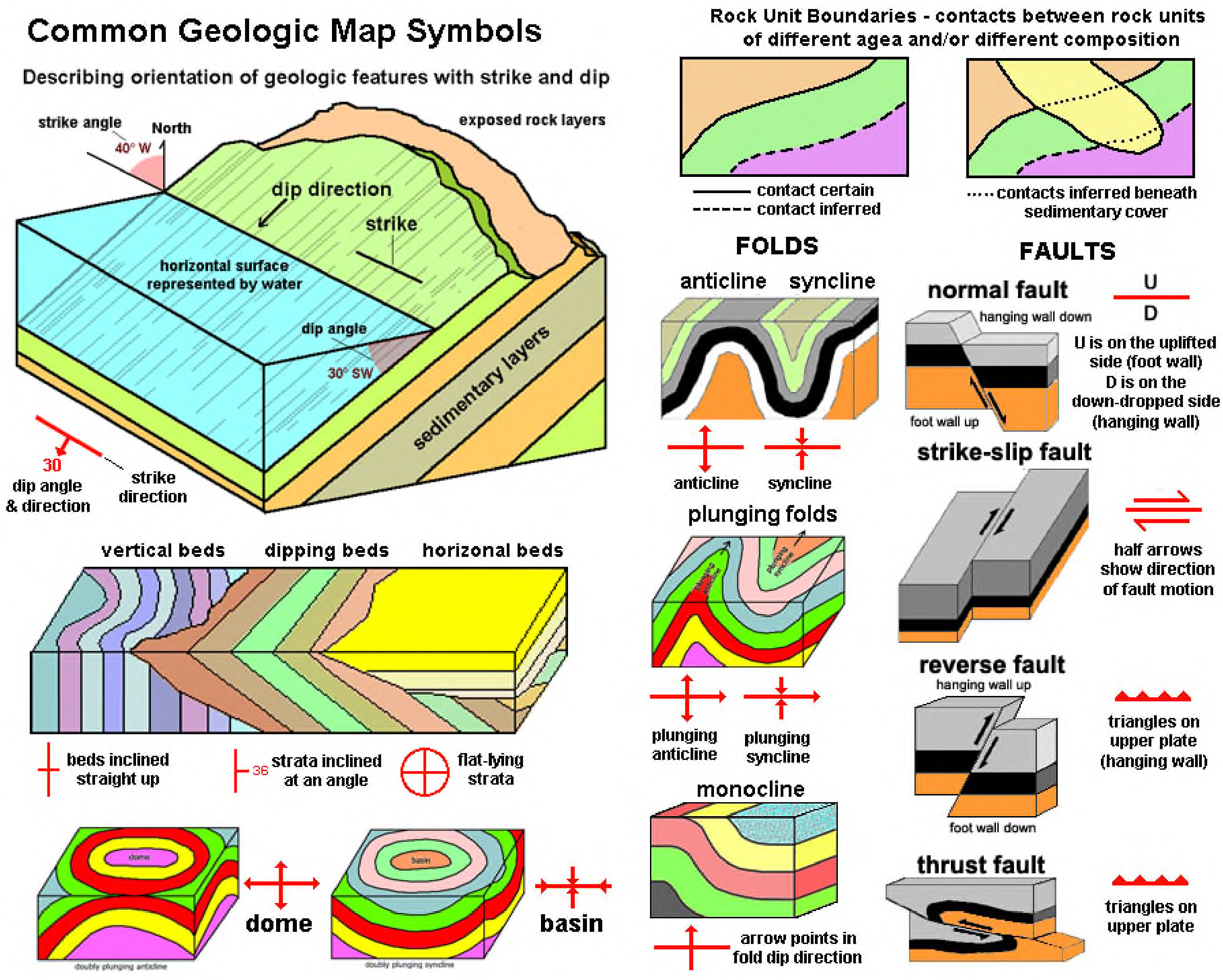


Figure 16 - Standard geologic map symbols (courtesy, AGI/NAGT Lab Manual, 11th ed.)

PART II - GEOLOGIC FAULTS: Indentifying Type, Orientation, and Stress Regime

The Major Types of Faults:

Faults are planar fractures of weakened rock in the Earth's crust where crustal displacement (slippage) occurs due to directed stresses. Every fault has a unique orientation in the ground and relative displacement motion across the fault – from vertical to horizontal in any cardinal direction. Every fault is subject to a certain type of crustal stress dictated by the regional tectonic plate setting. Faults are classified primarily by the relative motion or offset of the adjoin fault blocks – vertical (***dip-slip***) versus horizontal (***strike-slip***), or a combination of the two (***oblique-slip***). If the fault plane dips less than 90 degrees (not vertical), then the adjacent fault blocks can be assigned as ***hanging-wall*** (upper block) and ***foot-wall*** (lower block). See **Figure 17**.

A ***dip-slip fault*** – fault with vertical throw (offset motion) – is classified as a ***normal*** when the hanging wall moves downward relative to the footwall. A **dip-slip fault** is classified as a ***reverse* or *thrust*** when the hanging wall moves upward relative to the footwall. Normal faults form under prevailing tensional crustal stresses – most likely at divergent plate boundaries – where crust is extended and thinned. Reverse and thrust faults form under prevailing directed compressional crustal stresses – most likely at convergent plate boundaries – where crust is shortened and thickened. See **Figures 20 and 21**.

A **strike-slip fault** is classified as a ***right-lateral*** fault when the crustal block on the opposite side of the fault moves to the right. A strike-slip fault is classified as a ***left-lateral*** fault when the crustal block on the opposite side of the fault moves to the left. Strike slip faults form under shear stresses – most likely at transform plate boundaries – where crust is ground laterally past each other. See **Figures 20 and 21**.

An **oblique-slip fault** is a combination of dip-slip and strike-slip fault offset, where the offset motion is a combination of vertical and horizontal – essentially diagonal slip motion.

Below are illustrations of the various types of faults.

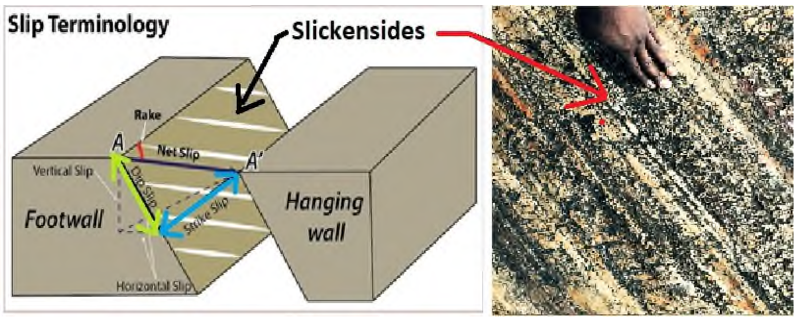


Figure 17 – Block Diagram of a Fault with Hanging and Footwall. Green arrow shows dip-slip direction; blue-arrow shows strike-slip direction. Image on right shows fault surface (plane) with polished, grooved slickensides.

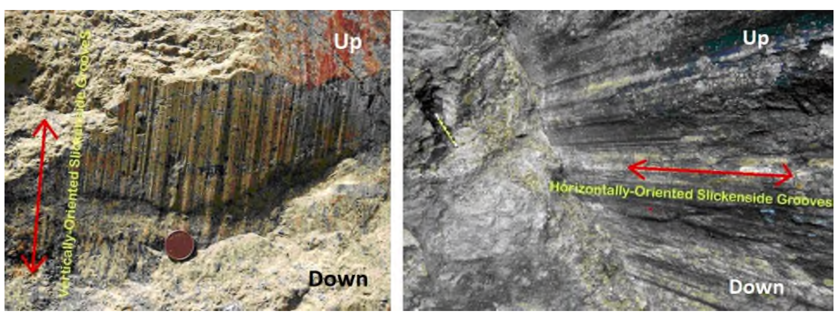


Figure 18 - Vertical-slip (Dip-slip) and Horizontal-slip (Strike-slip) Fault Slickensides

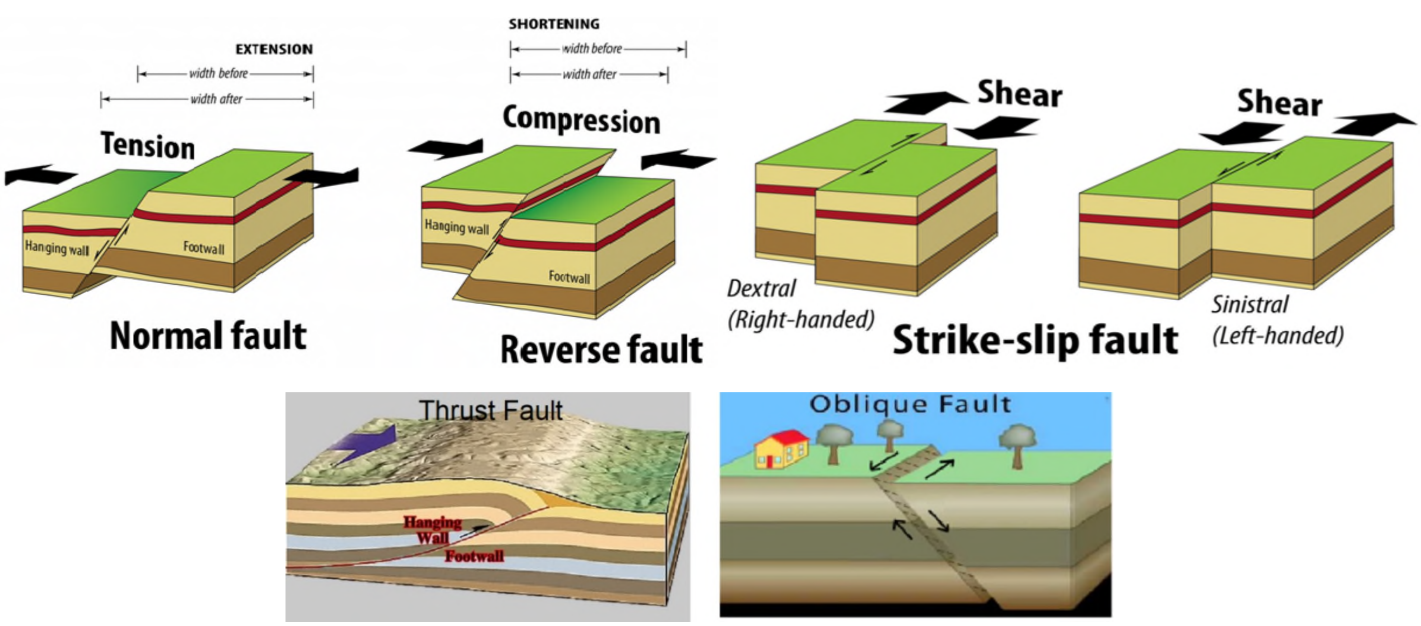


Figure 19 – The Major Types of Dip-slip and Strike-slip Faults

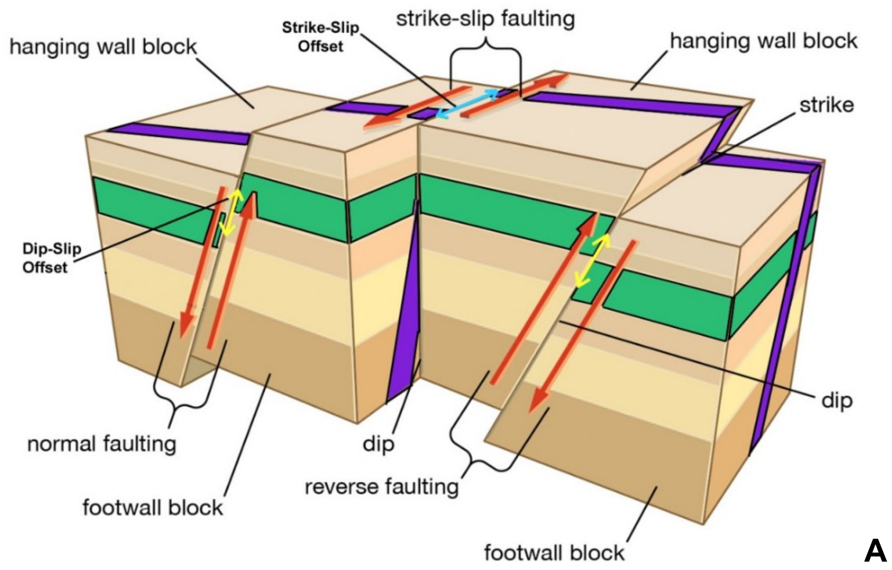


Figure 20 – Block Diagram of Three Faults that Illustrate Fault Offset

Green-colored marker bed is offset by dip-slip faults (yellow arrows show dip-slip offset). Purple-colored marker bed is offset by a strike-slip fault (blue arrow shows strike-slip offset). Marker bed offset is an indicator to which type of faulting occurred.

Important Structural Terms – Briefly define these fault-related terms below:

URL to a glossary of structural geology terms: http://www.geoscirocks.com/glossary_structural_terms.pdf

Foot Wall - ____

Hanging wall - ____

Normal Fault - ____

Reverse Fault - ____

Thrust Fault - ____

Right-lateral Strike-slip Fault - ____

Left-lateral Strike-slip Fault - ____

Oblique-slip Fault - ____

Slickensides - ____

Fault Offset Marker - ____

Structure Guidelines and Rules for Interpreting Faults: A fault is primarily classified based on how the two opposing crustal blocks move relative to each other along the fault. Determining what sort of fault movement has occurred on a given fault requires different means of documenting relative displacement across the fault. The primary means of establishing relative fault motion is by observing two aspects of the fault: 1. fault plane ***slickensides***, and 2. an ***offset marker***.

First, you need to find, grooved slickensides along the fault zone in order to document the type of slip on the fault: dip-slip, strike-slip, or oblique. Vertical (up-down) groves = dip-slip; horizontal (side-to-side) grooves = strike-slip; and diagonal (slanted) = oblique-slip. **See Figures 17 and 18.**

Secondly, you look for structural offset marker(s), which graphically illustrate(s) the relative displacement from pre-fault crust position to post-faulted crust position. Marker beds are usually in the form of a uniquely colored sedimentary bed or sequence of beds, lava flows, or intrusive dikes or sills – a package of disrupted rock that distinctly stands out from the rocks above and below in the stratigraphic column. **See Figure 20.**

For **dip-slip faults**, it's the relative vertical movement between the hanging wall and foot wall blocks that help determine whether a fault is a normal fault or a reverse fault. Therefore, you need to find an offset marker in cross-section view of the fault to determine the dip-slip (vertical) movement – looking for hanging wall up or down elative to foot wall. **See Figure 20.** Now to be sure that the offset you see in the cross-section is true vertical offset, you need to find grooved slickensides along the fault zone that indicate dip-slip movement, i.e. vertical grooves. **See Figure 18.**

For **strike-slip faults**, it's the relative horizontal movement between the opposing crustal blocks that help determine whether it's a right-lateral or a left-lateral strike-slip fault. Therefore, you need to find an offset marker in map view of the fault to determine the strike-slip (horizontal) movement – looking for whether the offset marker moved right or left on the opposite side of the fault relative to fixed block on the other side. See **Figures 19, 20**. Now to be sure that the offset you see in the map view is true horizontal offset, you need to find grooved slickensides along the fault zone that indicate strike-slip-slip movement, i.e. horizontal grooves. See **Figure 18.**

For oblique-slip faults, it's a combination of vertical and horizontal movement, so, offset markers need to be located and analyzed in both cross-section, and map view of the fault. And to be sure that the fault is oblique-slip in nature, you will need to check for slickensides with slated grooves. See **Figures 20.**

The above explanation, discussion, and illustration on determining the type of fault from a block diagram, map, cross-section, of field evidence can be formulated into the following set of structure rules for folds:

Structure Rules of Faults

1. Hanging wall is towards the fault dip direction; foot wall opposite to fault dip direction.

2. Hanging wall (HW offset marker in a cross-section view) *moves **DOWN*** relative to the foot wall (FW offset marker in a cross-section view) indicates a normal fault.

3. Hanging wall (HW offset marker in a cross-section view) *moves **UP*** relative to the foot wall (FW offset marker in a cross-section view) indicates a reverse or thrust fault.

4. A fault offset marker (seen in map view) that is displaced to the RIGHT in relation the other half on the offset marker (also seen in map view) on the side opposite the side of the fault indicates a right-lateral strike-slip fault.

5. A fault offset marker (seen in map view) that is displaced to the LEFT in relation the other half on the offset marker (also seen in map view) on the side opposite the side of the fault indicates a left-lateral strike-slip fault.

6. Slickenside grooves that are oriented vertical in fault scarp indicate dip-slip offset.

7. Slickenside grooves that are oriented horizontal in fault scarp indicate strike-slip offset.

Below are two exercises that will help you learn how to determine fault type by studying slickensides and marker beds.

Fault Exercise #1

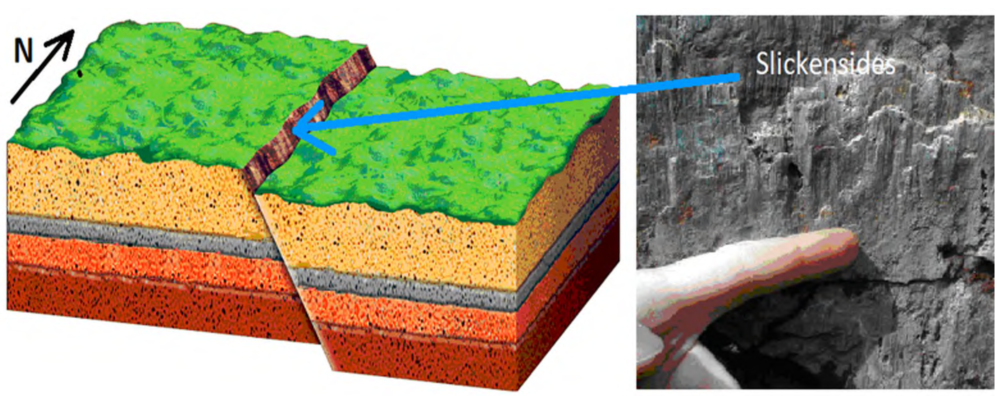


Figure 21 –Block Diagram for Fault Exercise #1

Study the fault plane, offset beds, and slickensides in the fault block diagram and image of **Figure 21** (to the left). Then answer the following questions following the fault rules of structure:

1) What direction is the strike of the fault? Hint: It's parallel to the fault scarp.

2) Which direction is the fault dipping? West, East, or vertical? Hint: It's perpendicular to the fault scarp.

3) How steeply dipping is the fault? High, medium, or low angle?

4) Which side of the fault in the above block diagram is the hanging wall block? West block or East block?

5) Based on the slickenside image of the fault plane, is this fault strike-slip or dip-slip?

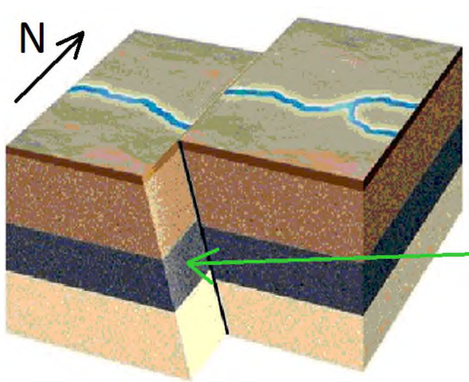
6) Based on the offset marker rock layers in cross-section, does this fault appear to be a strike-slip or dip-slip fault?

7) Based on the slickenside image of the fault plane AND the offset beds shown in cross-section, what specific type of fault is it?

8) What was the primary directed crustal stress that formed this fault? Tension, compression, or shear?

9) Which general type of plate boundary would this fault most likely form at? Convergent, divergent or transform?

Fault Exercise #2



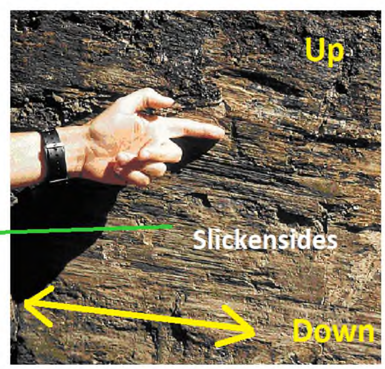


Figure 22 –Block Diagram for Fault Exercise #2

Study the fault plane, offset beds, and slickensides in the fault block diagram and image of **Figure 22** (left). Then answer the following questions:

11) What direction is the strike of the fault?   Hint: It's parallel to the fault line in map view.

12) Which direction is the fault dipping? West, East, or vertical?

13) How steeply dipping is the fault? High medium, or low angle?

14) Based on the slickenside image of the fault plane, is this fault strike-slip or dip-slip?

15) Based on the offset of the stream seen in map view, does this fault appear to be a strike-slip or dip-slip fault?

16) Based on the slickenside image of the fault plane AND the offset stream shown in map view, what specific type of fault is it?

17) What was the primary directed crustal stress that formed this fault? Tension, compression, or shear?

18) Which general type of plate boundary would this fault most likely form at? Convergent, divergent or transform?

19) After completing these fault exercises, do the fault rules seem to make sense? Are they helpful?

PART III - GEOLOGIC FOLDS: Determining the Type, Orientation, and Stress Regime of Faults

The Major Types of Folds:

As introduced in Part I, folds are deformational structures of buckled layers of rock formed deep in the Earth's crust by compressive directed stresses. Common in mountain-building events along convergent plate boundaries, folding of rock is a form of crustal shortening and thickening. Folding usually goes hand in hand with reverse and thrust faulting, the other forms of crustal shortening and thickening deformation under compressive conditions. The classification of folds is primarily based on which direction the rocks are buckled: if the rock is buckled upwards, the fold is called an ****anticline***"; if the rock is buckled downwards, the fold is called a "***syncline***". See **Figure 23** below for examples of an anticline and a syncline**.**

Use the URL's below to help you learn the different types of folds, and how to measure and identify them in block diagrams, maps, cross-sections, and out in the field:

1 - Fold Basics: https://www.youtube.com/watch?v=z_ZRC-i1y8k

2 - Classifying Folds: https://www.youtube.com/watch?v=uK1uRxq56iQ and https://www.youtube.com/watch?v=_7saYFzkIKs

3 - Folds: https://www.youtube.com/watch?v=536xSZ_XkSs

4 - Folds Tutorial Video: https://www.youtube.com/watch?v=6uf8SSJajyM

5 - Folding: https://www.youtube.com/watch?v=F2-fHccQUb0

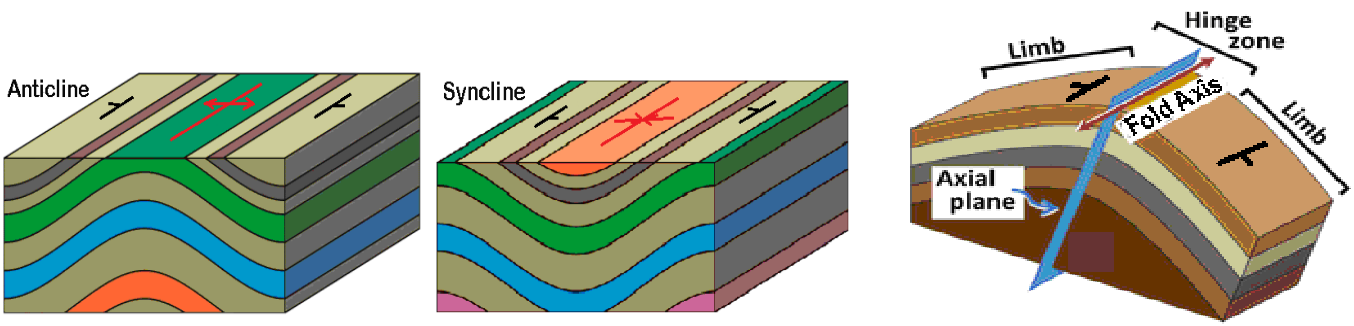


Figure 23 – The Two Basic Types of Folds and the Anatomy of a Fold

A fold has a unique anatomy that comes with unique terminology. Each fold has two sides, called "***limbs***". The two limbs meet each other along a planar abstraction called the "***axial plane***" – the surface formed when you slice the fold into two equal halves. All folds have a "***fold axis***" – a linear element - which is defined by the intersection of the fold (a curved plane) with the axial plane. See **Figure 23** above for fold anatomy terms.

A fold is considered to be a **horizontal or "non-plunging"** fold if its fold axis is horizontal. A fold is considered to be tilted or "**plunging**" if its fold axis is non-horizontal (dipping). Note that horizontal folds have a **stripped-looking** pattern of formation outcrops in map view, while in contrast, plunging folds have a **zig-zag-looking** pattern of formation outcrops. See **Figure 24** below for examples**.**

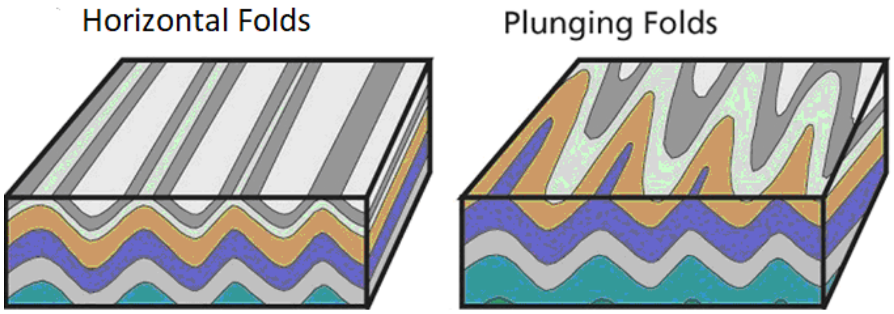


Figure 24 – Horizontal (Non-plunging) and Plunging Folds

Finally, folds can be categorized based on the attitude of the opposing limbs and orientation of the fold axis. Based on the above criteria, there are symmetrical, asymmetrical, and overturned folds. See **Figure 25** below for examples of these types of folds.

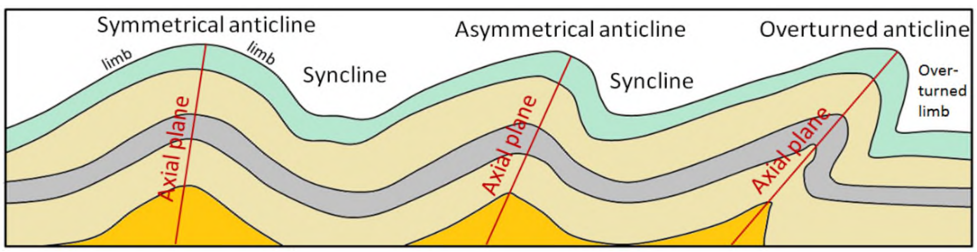


Figure 25 – Sub-classification of Folds Based on Limb and Axial Plane Dip

1) Important Structural Terms – Briefly define these fold-related terms below:

URL to a glossary of structural geology terms: http://www.geoscirocks.com/glossary_structural_terms.pdf

Anticlines - ____

Synclines - ____

Fold Limbs- ____

Axial Plane - ____

Fold Axis- ____

Horizontal Fold - ____

Plunging Fold - ____

Symmetrical Fold -____

Asymmetrical Fold - ____

Overturned Fold - ____

The above explanation, discussion, and illustration on determining the type of fault from a block diagram, map, cross-section, of field evidence can be formulated into the following set of structure rules for folds:

Structure Rules of Folds

1. Oldest rocks exposed in the center of eroded anticlines and domes.
2. Youngest rocks exposed in the center of eroded synclines and basins.
3. Horizontal folds form parallel sets of belt-like outcrop patterns.
4. Plunging anticlines form "V" of "U" shaped, belt-like outcrop patterns.
5. Anticline fold plunges toward closed end of "V" or "U" pattern.
6. Plunging synclines form "V" of "U" shaped, belt-like outcrop patterns.
7. Syncline fold plunges toward open end of "U" pattern.

Below are two exercises that will help you learn how to determine the type of fold by studying the map view and cross-sections, looking at outcrop formation orientation and age patterns, dip of bedding and fold axis orientation.

Fold Exercise #1

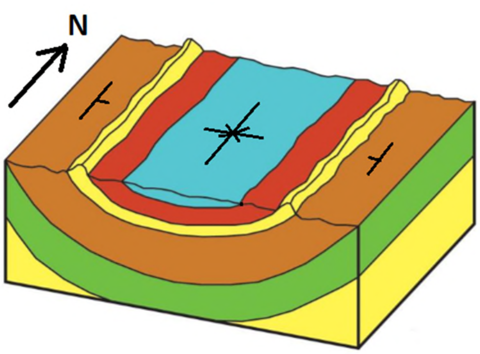


Figure 26 – Block Diagram for Fold Exercise #1

Instructions: Study the orientation and age relations and pattern of formation layering in the above fold block diagram found in **Figure 26** to the left. Then answer the following questions following the fold rules of structure:

1) What direction is the strike of the fold axis? Hint: it is parallel to the formation contacts in map view.

2) Which direction is the WEST limb of the fold dipping? Is it outwards and away from the fold axis, or inwards and towards the fold axis?

3) How steeply dipping is the WEST limb of fold? High angle dip? Medium angle? Or low angle?

4) Which direction is the EAST limb of the fold dipping? Is it outwards and away from the fold axis, or inwards and towards the fold axis?

5) How steeply dipping is the WEST limb of fold? High angle dip? Medium angle? Or low angle?

6) Looking at the map view, where are the OLDEST rocks of the fold found? Are they along the fold axis, or furthest away from the fold axis? Where are the YOUNGEST rocks of the fold found?

7) Which type of fold is it? Anticline or syncline? Which structure rules confirm your answer?

8) Which type of fold is it? Symmetrical, asymmetrical, or overturned? How can you tell?

9) Which type of fold is it? Horizontal (non-plunging) or plunging? Check the cross section of the block that is PARALLEL to the fold axis. Are the rock layers horizontal or tilted? Which structure rules confirm your answer?

10) What was the primary directed crustal stress that formed this fold? Tension, compression, or shear?

11) From which directions were the crustal stresses being applied to form this fold? North-South? East-West?

12) Which general type of plate boundary would this fold most likely form at? Convergent, divergent or transform?

Fold Exercise #2

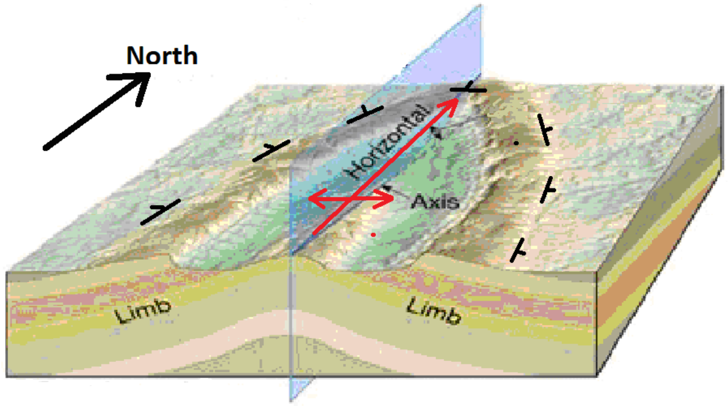


Figure 27 – Block Diagram for Fold Exercise #2

Instructions: Study the orientation and age relations and pattern of formation layering in the above fold block diagram found in **Figure 27** to the left. Then answer the following questions following the fold rules of structure:

1) What direction is the strike of the fold axis?

2) Which direction is the WEST limb of the fold dipping? Is it outwards and away from the fold axis, or inwards and towards the fold axis?

3) How steeply dipping is the WEST limb of fold? High angle dip? Medium angle? Or low angle?

4) Which direction is the EAST limb of the fold dipping? Is it outwards and away from the fold axis, or inwards and towards the fold axis?

5) How steeply dipping is the WEST limb of fold? High angle dip? Medium angle? Or low angle?

6) Looking at the map view, where are the OLDEST rocks of the fold found? Are they along the fold axis, or furthest away from the fold axis? Where are the YOUNGEST rocks of the fold found?

7) Which type of fold is it? Anticline or syncline? Which structure rules confirm your answer?

8) Which type of fold is it? Symmetrical, asymmetrical, or overturned?

9) Check the cross section of the block that is PARALLEL to the fold axis. Are the rock layers horizontal or tilted?

10) Which type of fold is it? Horizontal (non-plunging) or plunging? Which structure rules confirm your answer?

11) What was the primary directed crustal stress that formed this fold? Tension, compression, or shear?

12) From which directions were the crustal stresses being applied to form this fold? North-South? East-West?

13) Which general type of plate boundary would this fold most likely form at? Convergent, divergent or transform?

14) After completing this exercise, do the structure rules seem to make better sense? Were they helpful?

PART IV – IDENTIFYING GEOLOGIC STRUCTURES IN THE FIELD

Identifying Real-Life Faults and Folds:
Parts II and III introduced you to two of the most common forms of crustal deformation in the Earth's crust – faults and folds. You learned what sorts of particular structural features and spatial relations that faults and folds have, and how to use that information to identify geological structures in a block of crust – whether in a block diagram, geology map, cross-section, or while mapping the actual Earth's surface in the field. In Part IV, you will utilize your newly acquired structural geology knowledge and skills to identify real geologic structures in road cuts, cliffs, and aerial shots. Use the list of structural rules below to help you identify the structure(s).

The Rules for Interpreting Geologic Structures

1) Strike of beds is always parallel to the direction of the contacts.

2) Rock layers dip towards the youngest exposed rock layers.

3) Steeper the dip of the layer, the more narrow the width of its outcrop.

4) Hanging wall is towards the fault dip direction; foot opposite to fault dip direction

5) Hanging wall *moves up* relative to foot wall in reverse and thrust faults.

6) Hanging wall *moves down* relative to foot wall in normal faults.

7) Slickenside grooves that are oriented horizontal in fault scarp indicate strike-slip offset.

8) Slickenside grooves that are oriented vertical in fault scarp indicate dip-slip offset.

9) Oldest rocks exposed in the center of eroded anticlines and domes.

10) Youngest rocks exposed in the center of eroded synclines and basins.

11) Horizontal folds form parallel sets of belt-like outcrop patterns.

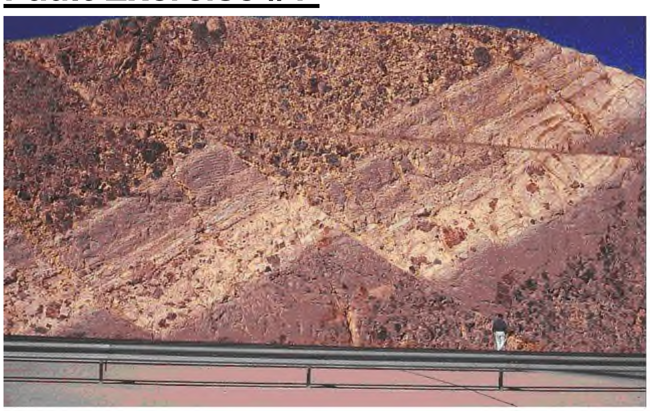
12) Plunging anticlines form "V" of "U" shaped, belt-like outcrop patterns.

13) Anticline fold plunges toward *closed* end of "V" or "U" pattern.

14) Plunging synclines form "V" of "U" shaped, belt-like outcrop patterns.

15) Syncline fold plunges toward *open* end of "U" pattern.

Fault Exercise #1



Slickensides

Figure 28 –Road-Cut Image for Exercise #1

Instructions: Study the orientation of rock formations in the above road cut in **Figure 28** (left). Note that the slickensides were found to have vertically-oriented grooves and striations. Answer the following questions for **Figure 28**.

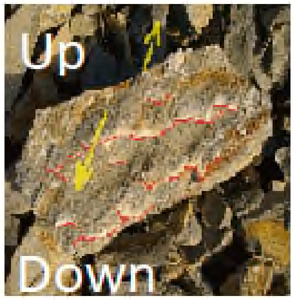
1) Is this a dip-slip or strike-slip fault?

2) Did the hanging wall move up or down relative to the footwall?

3) Name this geologic deformation structure. Be as specific as possible.

4) Which of the three types of directed crustal stress most likely caused this structure to form?

Fault Exercise #2



Slickensides

Figure 29 –Cliff Face Image for Exercise #2

Instructions: Study the orientation of rock formations in the above cliff face in **Figure 29** (left). Note that slickensides were found to have vertically-oriented grooves and striations. Answer the following questions for **Figure 29**.

1) Is this a dip-slip or strike-slip fault?

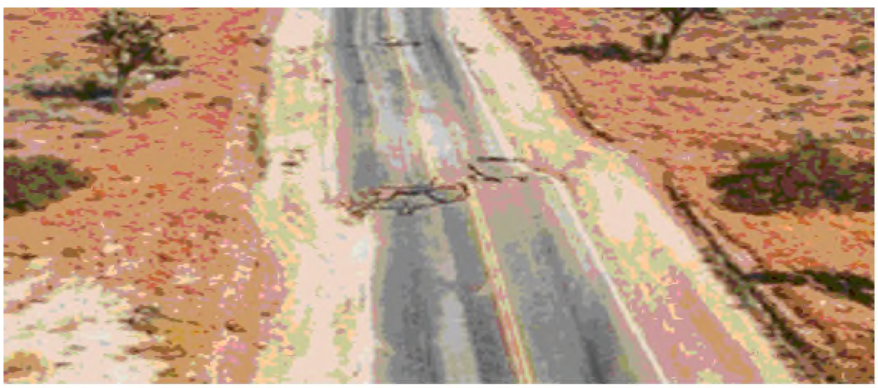
2) Did the hanging wall move up or down relative to the footwall?

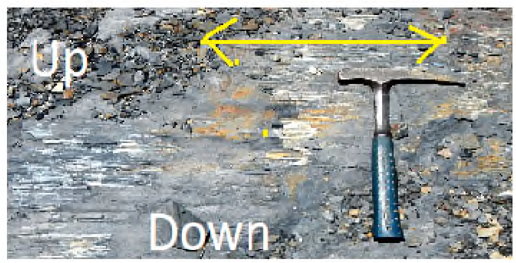
3) Name this geologic deformation structure. Be as specific as possible.

4) Which of the three types of directed crustal stress most likely caused this structure to form?

5) Which plate tectonic boundary did this structure most likely form at?

Fault Exercise #3





Slickensides

Figure 30 –Aerial Image of Road for Exercise #3

Instructions: Study the orientation of road in the above aerial shot in **Figure 30** above. Note that slickensides were found to have horizontally-oriented grooves and striations. Answer the following questions for **Figure 30**.

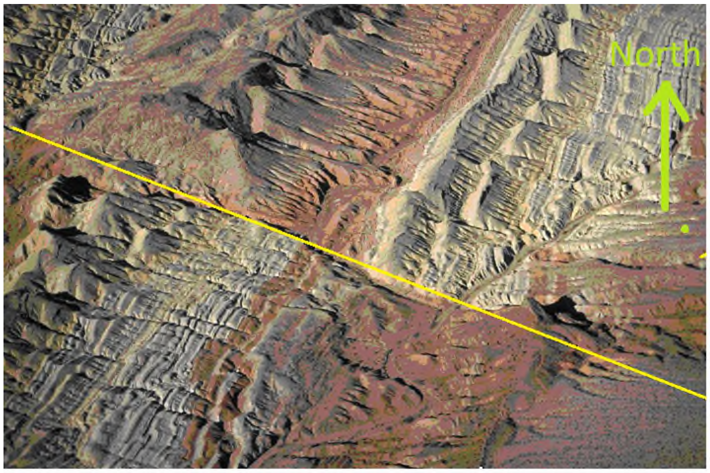
1) Is this a dip-slip or strike-slip fault?

2) Is this right lateral or left-lateral?

3) Which of the three types of directed crustal stress most likely caused this structure to form?

4) Which plate tectonic boundary did this structure most likely form at?

Fault Exercise #4



Slickensides

Figure 31 – Aerial Image of Mountains for Exercise #4

Instructions: Study the orientation of road in the above aerial shot of a region of China in **Figure 31** above. The yellow line coincides with the strike of the fault. Note that slickensides were found to have horizontally-oriented grooves and striations. Answer the following questions for **Figure 31**.

1) Is this a dip-slip or strike-slip fault?

2) Is this right lateral or left-lateral?

3) Which of the three types of directed crustal stress most likely caused this structure to form?

4) Which plate tectonic boundary did this structure most likely form at?

Fold Exercise #1

Figure 32 – Road Cut Image for Exercise #5

Instructions: Study the rock formation in the above road cut image in **Figure 32** to the left. Answer the following questions

1) Is this geologic deformation structure an anticline or a syncline?

2) Is this geologic deformation structure a symmetrical, asymmetrical, or overturned?

3) Which of the three types of directed crustal stress most likely caused this structure to form?

4) Which plate tectonic boundary did this structure most likely form at?

Fold Exercise #2

Figure 33 – Road Cut Image for Exercise #6

Instructions: Study the rock formation in the above road cut image in **Figure 33** to the left. Answer the following questions:

1) Is this geologic deformation structure an anticline or a syncline?

2) Is this geologic deformation structure a symmetrical, asymmetrical, or overturned?

3) Which of the three types of directed crustal stress most likely caused this structure to form?

4) Which plate tectonic boundary did this structure most likely form at?

Exercise #7

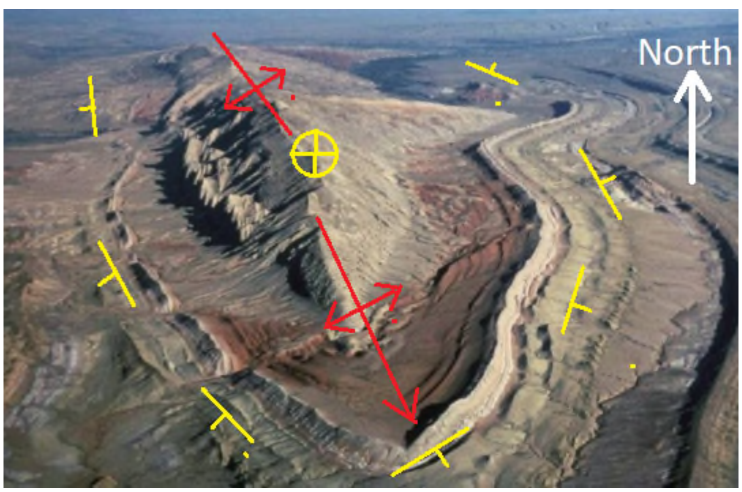


Figure 34 –Aerial Image of a Mountain for Exercise #7

Instructions: Study the rock formations in the above aerial shot in **Figure 34** to the left. Note the yellow strike and dip symbols along with red structural symbols. Also note that the oldest rocks are found along the mountain top.

1) Is this geologic deformation structure an anticline or a syncline?

2) Is this geologic deformation structure plunging or non-plunging? If plunging, which direction?

3) Which of the three types of directed crustal stress most likely caused this structure to form?

4) Which plate tectonic boundary did this structure most likely form at?

STRUCTURAL GEOLOGY LAB REFLECTION:

Directions: Write a 3-point reflection of the lab activity, explaining its purpose, the methods used, the results obtained, and a brief personal reflection of what you enjoyed and learned about doing this structural geology lab (*3 points possible*). Answer the following 3-point question reflection set.

1) *What was the purpose of this lab? What did you actually discover and learn during this lab?*

2) *What did you enjoy most about this lab? Also, what was challenging or thought-provoking?*

3) *What are your constructive comments about the design and execution of this lab? What's good? What's bad? Offer suggestions for making the lab better.*