

Chapter 6

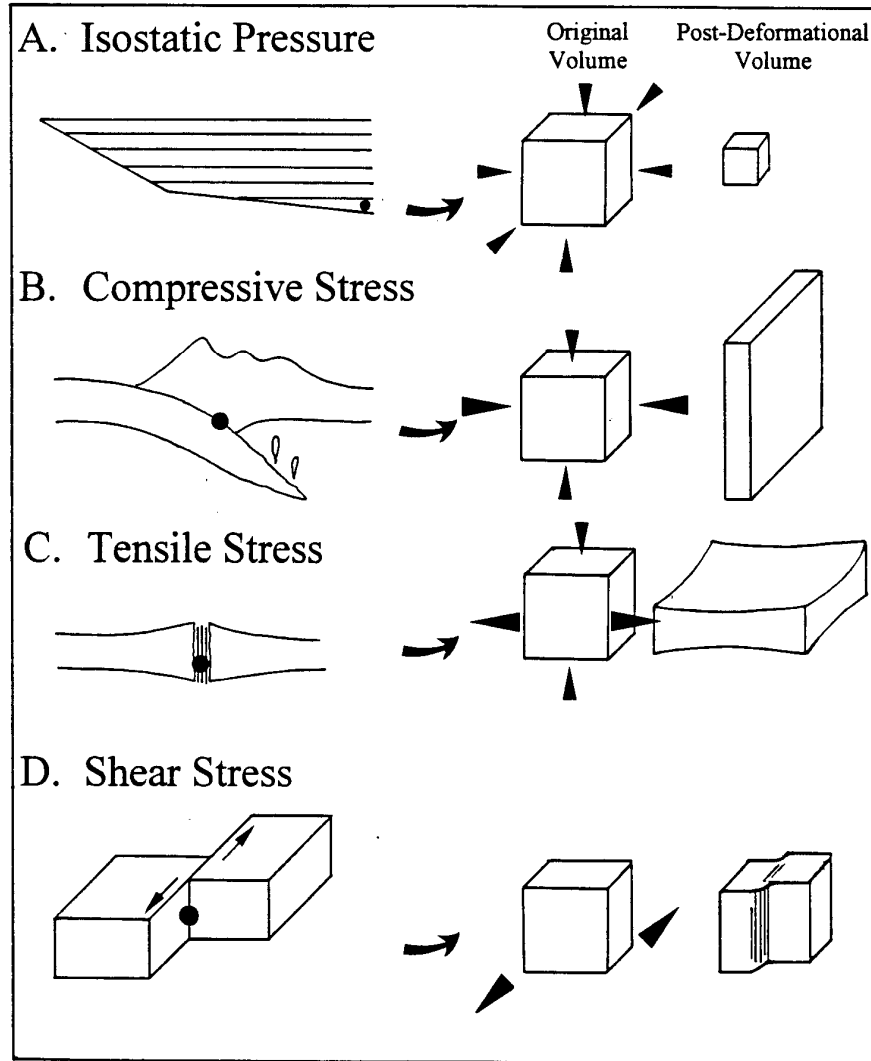
Geological Maps 2: Folded Strata

The same factors responsible for metamorphism (chiefly pressure and temperature) are also responsible for rock deformation; however, the actual processes of deformation are complex which necessitates additional discussion here. If you take a volume of strata and place it deep inside the Earth, those rocks will experience **pressure** related to the mass of the overlying rocks. Geologists refer to this as the **confining pressure**. Confining pressure is generally **isostatic** (i.e., it is more or less uniform in all directions) and in general, the deeper you go, the higher it becomes. Since the strata are equally squeezed from all sides, the result is a net decrease in volume, but there is no change in shape of the rock volume (Figure 6.1).

Not all pressure in the interior of the Earth is isostatic. Along a convergent plate boundary, for example, the pressure is directed between the two colliding plates. Pressure that is non-isostatic or **directed** is regarded as **stress**. There are three main types of stress that can affect rocks. **Compressive stress** (or **compression**) occurs when rocks are squeezed together such as along convergent plate boundaries and subduction zones (Figure 6.1b). **Tensional shear** (or **tension**) occurs when rocks are pulled apart (Figure 6.1c). This is the major force operating along divergent plate boundaries such as

Figure shows an ideal section across the Uintah Mountains. The dashed lines show the pre-erosion level of the mountains. From: LeConte, J., 1905. Elements of Geology. D. Appleton and Co., New York, NY, 667p.

Figure 6.1: Effects of pressure on the volume and shape of rock strata.



the Mid-Atlantic Ridge. The third type of stress, **shear**, occurs when rocks slide past one another (Figure 6.1d). This occurs along transform fault boundaries such as the San Andreas Fault in California or the Alpine Fault in New Zealand. It is important to note that while compression, tension and shear do operate along plate boundaries, they are by no means restricted to these features. Stress can occur anywhere, provided that circumstances permit it. The earthquake that occurred north of Mobile in 1997 resulted from stress that built up wholly within a continent not at a plate boundary. Like stress, earthquakes can also occur anywhere on the Earth.

6.1 Types of Rock Deformation

When rocks experience stress (compression, tension or shear), they respond to it by deforming. The rocks tend to give a little bit, especially at the beginning of the deformation. If the pressure is eased during this period of **elasticity**, the rocks return to their original volume and shape. If however, the stress builds up past the **elastic limit** of the strata, deformation becomes permanent.

Rocks will permanently deform in one of two ways, depending upon their properties and the confining pressure they experience. Strata will **break** if the rocks behave in a **brittle** fashion and/or the confining pressure is low. Brittle deformation is particularly common in rocks that contain hard and non-giving minerals like quartz (e.g., quartz arenite sandstone) or calcite (e.g., limestone), that are shallowly buried (low confining pressure). It results in fractures, joints and faults, features that you will have the pleasure (Ha!) of dealing with in Chapter 7.

If strata are **ductile** (like modeling clay), and/or the confining pressure is high, the deformation is more likely to result in **bending** or **folding**. Rocks containing pliable minerals like gypsum (evaporites) or clays (shales), or rocks that are deeply buried (>10 km depth) become folded when subjected to stress. There are numerous types and shapes of folds, but most can be classified into three basic types.

6.2 Types of Fold Structures

The three broad classes of folds are (1) **anticlines**, (2) **synclines** and (3) **monoclines**. The term anticline is used for any fold structure consisting of two **limbs** spread apart in a downward fashion (concave downward; Figure 6.2a). Synclines are bi-limbed folds where the limbs open upward (concave upward; Figure 6.2b) Monoclines, as the name implies, have only one limb (Figure 6.2c).

The symmetry and orientation of these fold structures can be highly variable. They can be **symmetrical** (Figure 6.2a,b), **asymmetrical** or **overturned** (Figure 6.3). In some instances, anticlines and synclines may lie on their sides. These folds are said to be **recumbent** (Figure 6.3c). They may also be inclined rather than horizontally-

Figure 6.2: Schematic diagrams of ideal fold structures. (A) symmetrical anticline; (B) symmetrical syncline; (C) monocline.

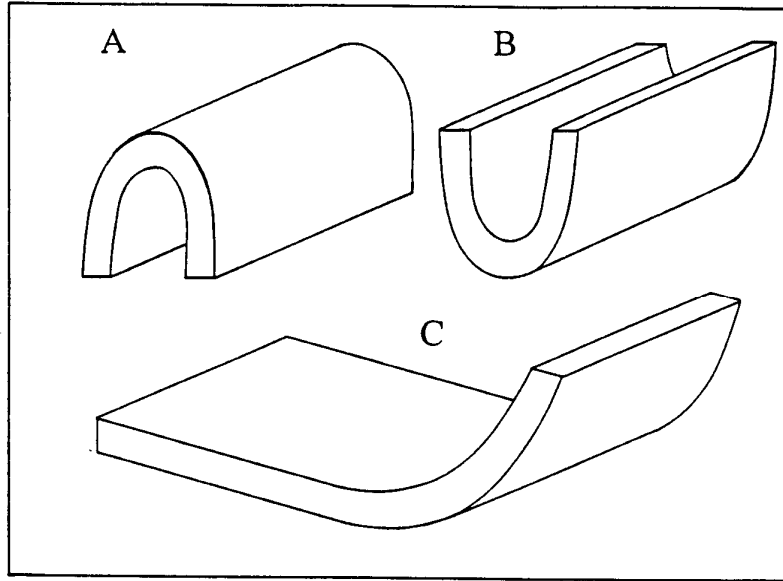
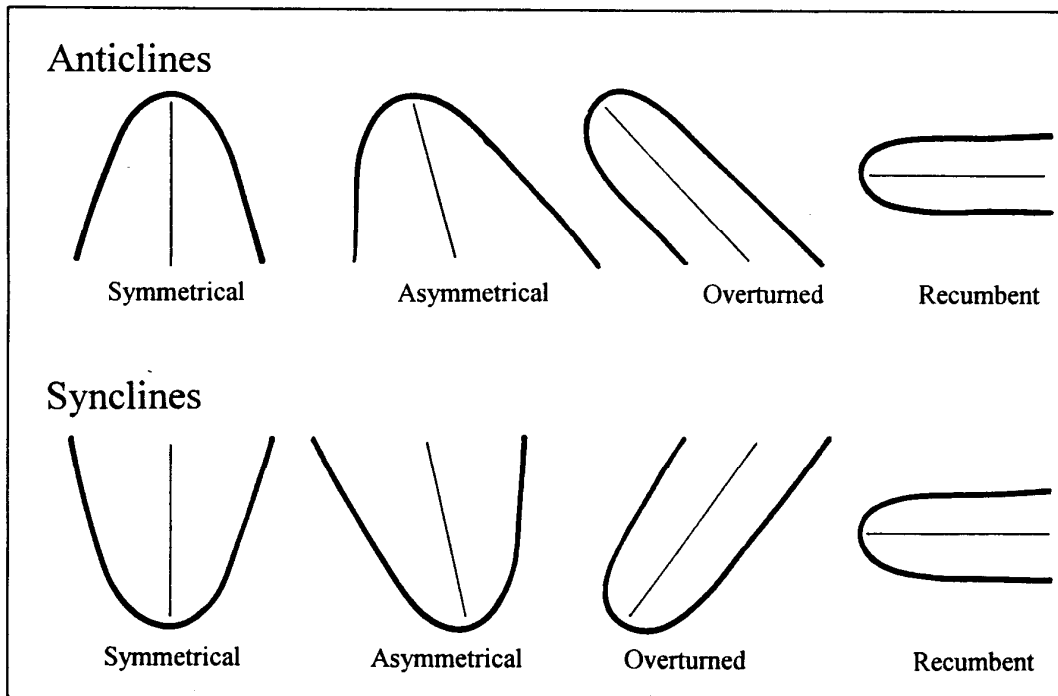


Figure 6.3: Schematic diagrams of symmetrical, asymmetrical, overturned and recumbent anticlines and synclines.



orientated. This class of folds are said to be **plunging** and they are among the most difficult of the geological structures to visualize and to interpret (Figure 6.4).

Two other fold structures that give students the heebie jeebies are **domes** and **basins** (Figure 6.5). These geological features are perhaps best described as doubly folded folds. Domes consist of strata that have been folded upwards where as basins consist of strata that is inclined downwards (down-warped). Domes can be very large, in fact whole mountain ranges may consist of a single dome structure (e.g., the Ozark Mountains). Basins are formed through a much different mechanism more related to sedimentation than to simple rock deformation. Down-warping is produced by **subsidence** which may or may not be tectonic in origin. The main point is that down-warping produces a depression which gradually becomes filled in with sediment. The Law of Superposition applies here. The oldest strata occurs at the bottom of the basin (e.g., Figure 6.5).

Folds are really not all that difficult to interpret, but some of the terminology is trying. The next section summarizes everything that you will need to know to identify and label vital components of folds on block diagrams. Section 6.5 which follows it summarizes

Figure 6.4: Schematic diagrams illustrating horizontal and plunging anticlines.

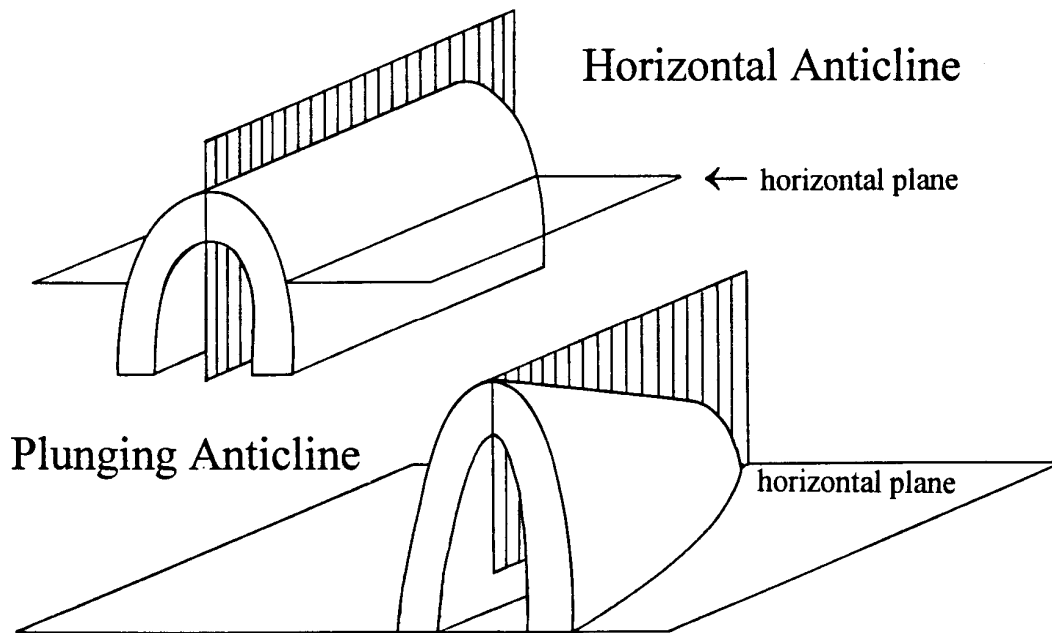
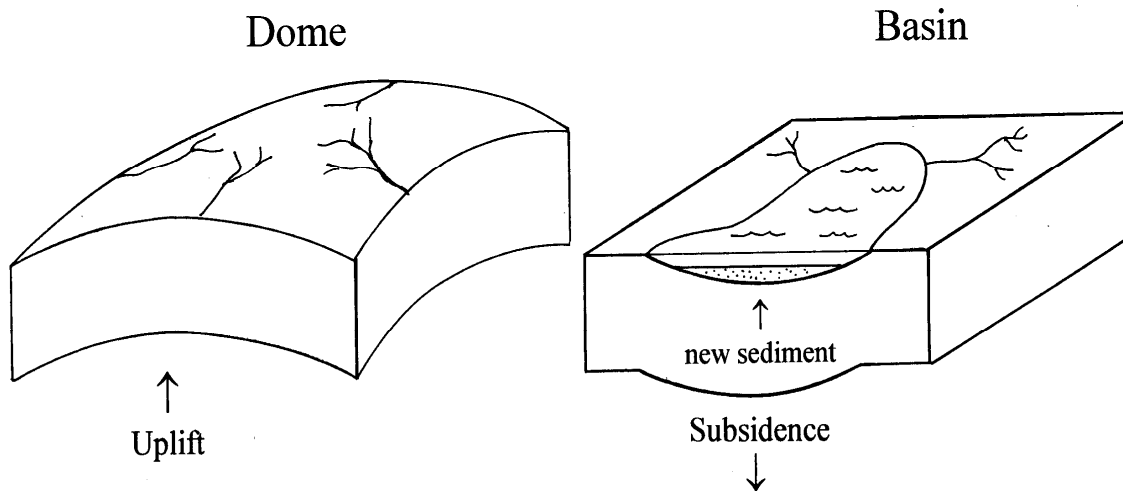


Figure 6.5: Schematic diagrams illustrating a dome and a basin.



vital information by which to recognize more complex fold structures on geological maps. Refer to Table 5.3 for additional fold symbols.

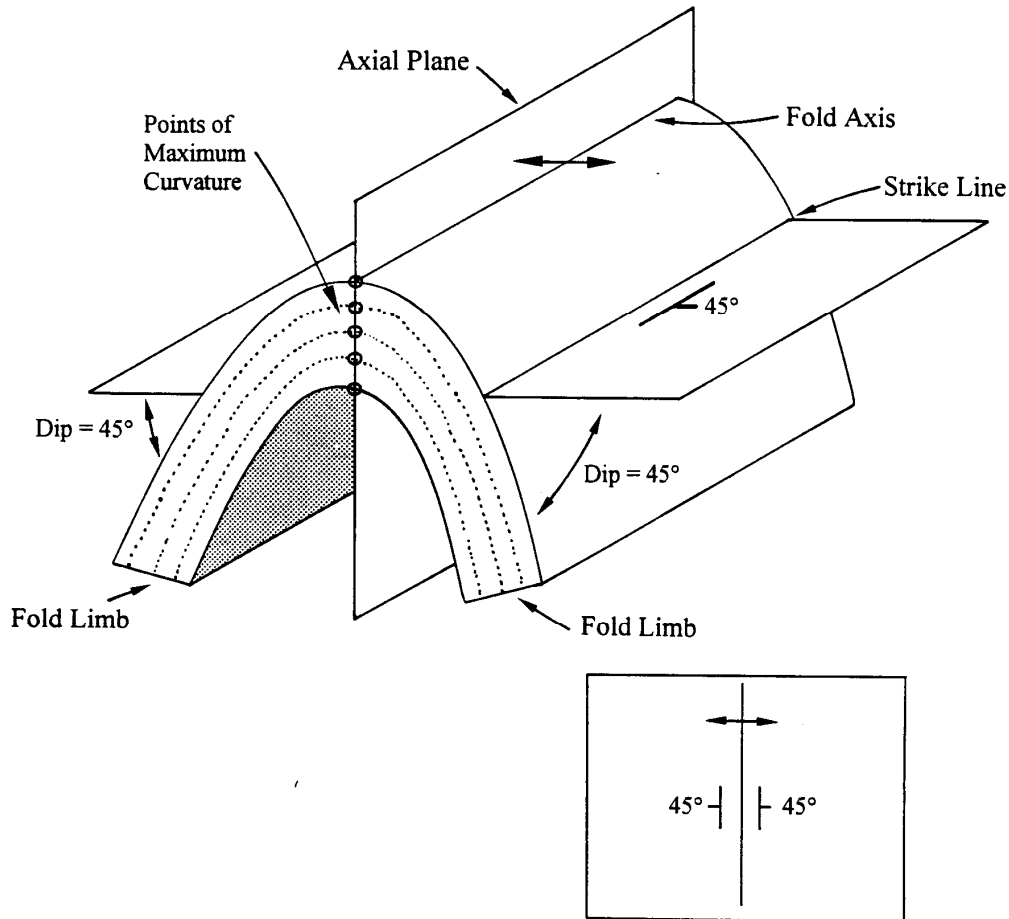
6.3 Folds on Block Diagrams

Figure 6.6 shows a schematic diagram of an anticline with key components labeled. First, observe that the anticline is symmetrical; both limbs dip the same amount, but in opposite directions. In a way, you can consider fold limbs to be two sets of inclined strata which dip in different. Each limb can be described using a single strike and dip

symbol (Figure 6.6). Note, since the fold is symmetrical, the dips are equal. Had the fold been asymmetrical, the dips would have been different (Figure 6.7). Overturned folds would have dips that trend in the same direction (Figure 6.7). Another thing to note is that the strike for both limbs in all of these examples are parallel. This is characteristic of all folds that have a horizontal disposition (such as the example in Figure 6.6). As you will see shortly, plunging folds do not share this characteristic.

To properly label a fold, some additional information is required. Both limbs of the fold are connected together. At one point in each layer, the bedding is actually horizontal (points labeled with 'o's in Figure 6.6). This position is known as the **point of maximum curvature** as it marks the point where the dip of the strata changes direction. If you connect each point in each layer, you can define an **axial plane** which divides the fold into two components. For the symmetrical anticline in Figure 6.6, the axial plane is

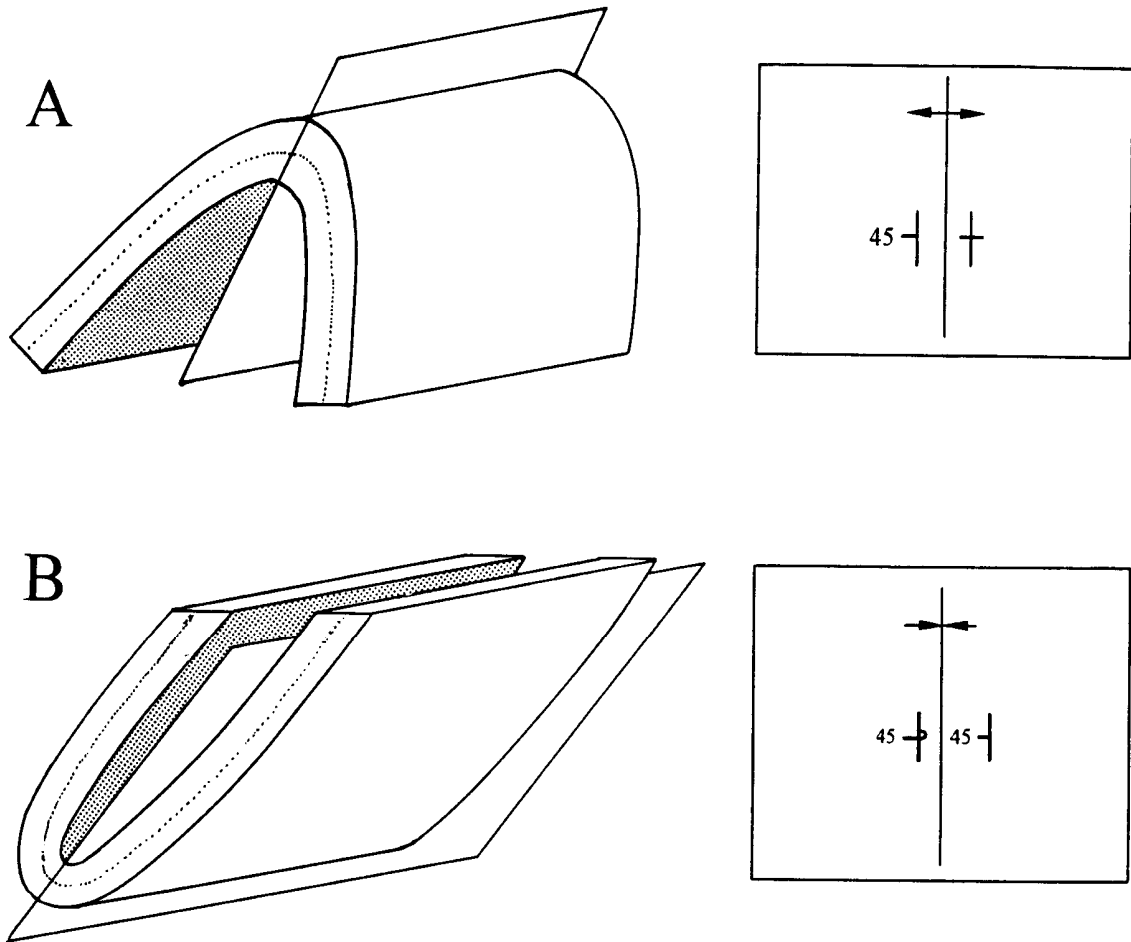
Figure 6.6: Oblique schematic of a horizontal symmetrical anticline with all important parts and features labeled. Refer to Table 5.1 and to the text in Chapter 6 for discussion of each of these features. The inset summarizes a plane-section (map view) of the anticline. Note the orientation of the strike and dip symbols for each fold limb relative to the fold axis.



orientated in a vertical fashion. An asymmetrical or overturned fold may have an inclined axial plane (Figure 6.7) and axial planes may even be horizontal if the fold is recumbent.

Axial planes are vital for describing the orientation of folds, but they are hard to visualize as a surface expression on plane sections (e.g., geological maps). Fortunately (or unfortunately depending upon your opinion of geological maps), axial planes do leave their mark. Remember anything from high school geometry? When any two planes intersect, they do so in a line. The axial plane (a plane) usually intersects the surface of

Figure 6.7: Schematic block diagrams and plane sections of non-symmetrical folds. (A) asymmetrical anticline; (B) overturned syncline. Compare the orientations of the strike and dip symbols for each fold with those in Figure 6.6.



the Earth (another plane) and they do so in a line called the **fold axis** (Figure 6.6). There are two symbols used to identify fold axes depending upon whether the structure is an anticline or a syncline (Table 5.3). The symbols are modified for instances when the folds plunge.

Plunging folds, as stated previously, are inclined relative to a horizontal plane such as the surface of the Earth (Figure 6.4). This wasn't explained all that well earlier because it was necessary to first explain the concept of axial planes and fold axes. The previous example (Figure 6.6), was a horizontal anticline. Note that the fold axis is also

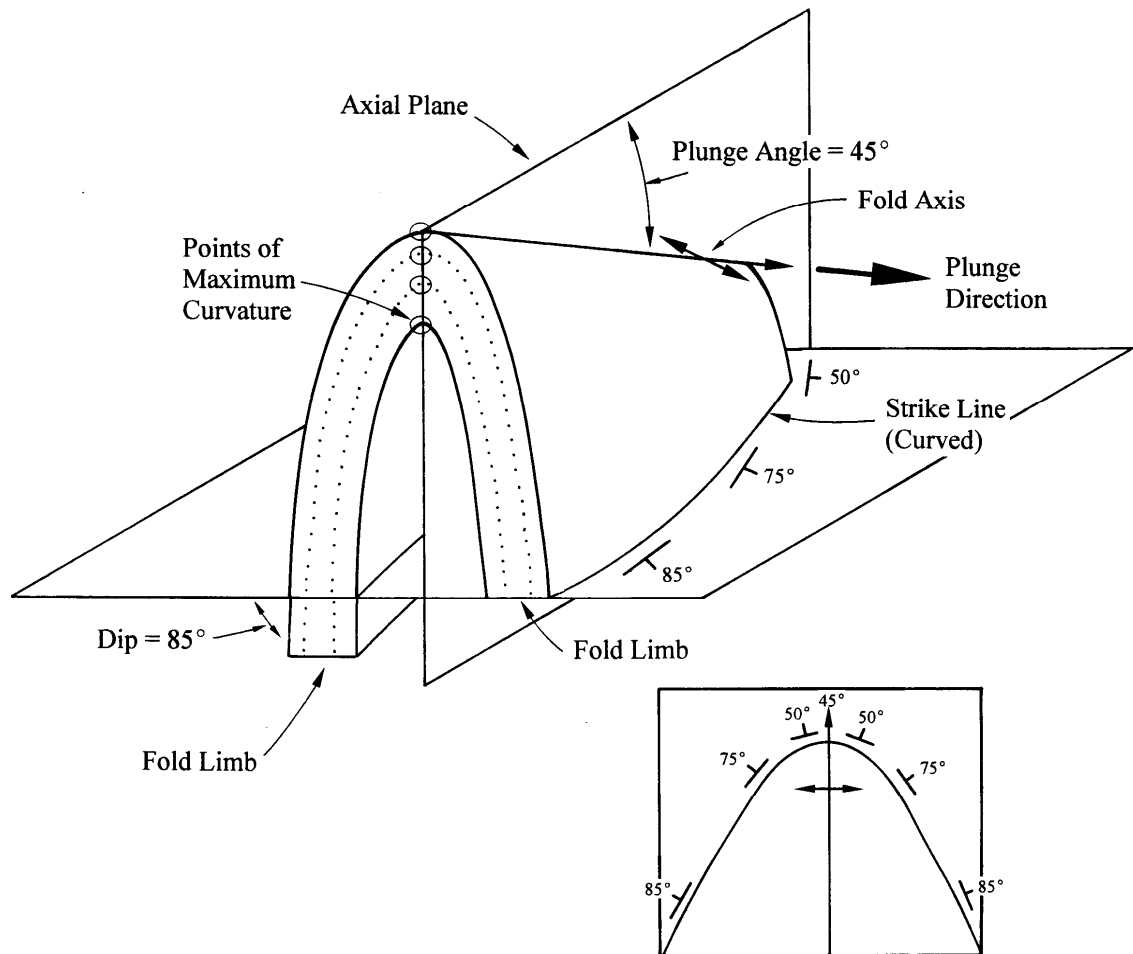
horizontal. When the fold is plunging, it follows that the fold axis will also plunge (Figure 6.8). An arrow is added to the fold axis to indicate the direction of plunge (Table 5.3). The **angle of plunge** is measured from the horizontal plane downward to the fold axis. Now for the hard part. Unlike horizontal folds, plunging folds have varying strikes and dips for their limbs depending upon proximity to the fold axis (Figure 6.8). The strike of the limbs parallel the fold axis only in areas at some distance from the "**nose**" (the point of the geological map where the fold curves back on itself). The strike direction changes as one approaches the nose. Right at the nose (on top of the fold axis), the strike is exactly perpendicular to the plunge direction of the fold. The amount of dip also varies. It equals the inclination of the fold limbs when the strike parallels the fold, but equals the inclination of the plunge in the nose of the fold. Confused yet? I find it easier to simply visualize the pattern of strike and dip when dealing with plunging fold structures. Plunging anticlines are identified by outward pointing dips whereas plunging synclines display an inward dipping trend (Figure 6.9). Domes and basins also display this pattern of strike and dip albeit in a more complete fashion (Figure 6.10).

6.4 Fold Structures and Erosion

So far, we have avoided discussing the effects of erosion on geological structures, but I'm afraid that we have no choice but to deal with it now. The folds that were discussed in the previous sections were ideal. However, in the real world, folds, like any type of topographical feature, are subject to erosion. An anticline (a topographic high) tends to have its top (or **hinge**) removed by erosion because this is where the elevation is highest (Figure 6.11). This exposes deeper portions of the fold's core. For a syncline, erosion tends to focus on the outer part of the limb because they are higher than the hinge area. If we assume that the surface of the Earth is "roughly horizontal", erosion of folds results in a pattern of repeated strata. In an anticline, the oldest strata occurs directly below the fold axis and it gets progressively younger in both directions away from the fold axis. In a syncline, the strata is youngest directly below the fold axis and is gets older symmetrically away from it. It should be pointed out that different rock layers vary in susceptibility to erosion and weathering. A quartz arenite sandstone is much more resistant than a shale, so when mixed strata like these are folded, a pattern of ridges and valleys develop (Figure 6.11). These patterns are sometimes evident at the surface of the Earth. Through use of aerial photography and satellite imagery, they can

be traced for many miles across vast portions of mountain ranges. Remote sensing analysis such as this

Figure 6.8: Oblique schematic of a plunging symmetrical anticline with all important parts and features labeled. The inset summarizes a plane-section (map view) of the anticline. Note the variation in orientation of the strike and dip symbols for each fold limb relative to the fold axis and the plunge of the fold axis.



has demonstrated one major thing about real folds; they seldom occur as isolated structures. More often than not, folds occur in complex sequences of anticlines and synclines. Interpreting these complexes is where the real fun begins in structural geology.

Figure 6.9: Strike and dip trends of strata associated with a (A) plunging anticline and (B) a plunging syncline.

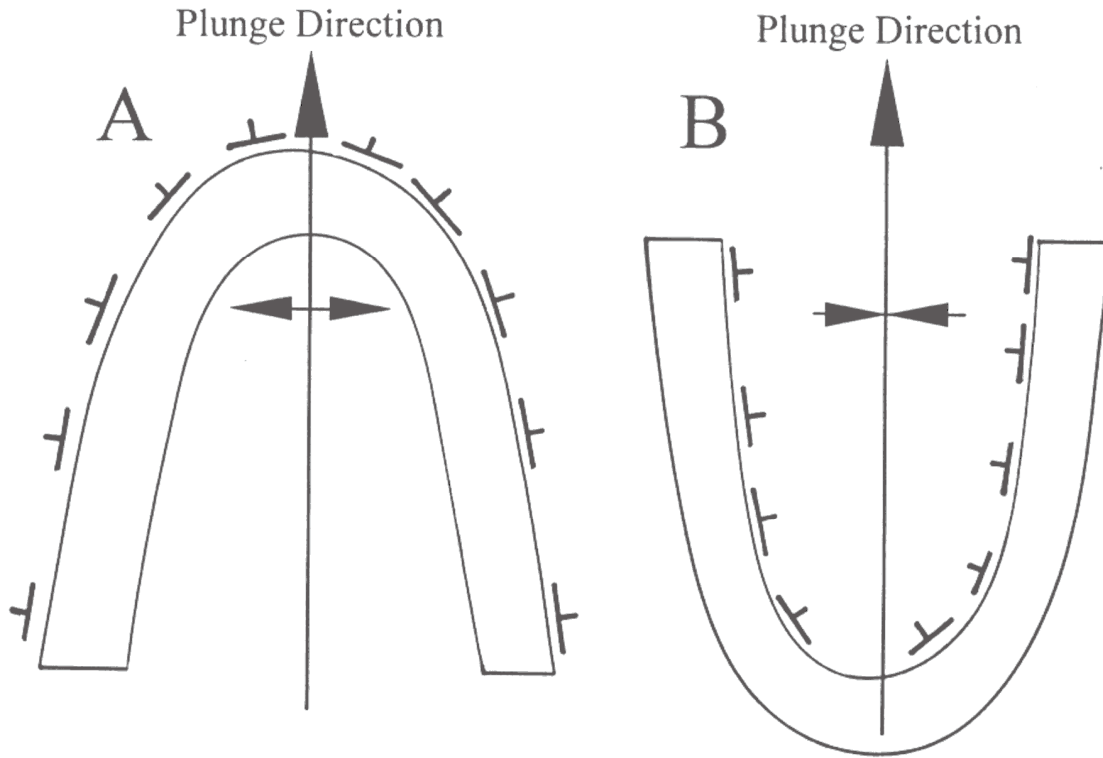


Figure 6.10: Strike and dip trends of strata associated with a (A) dome and (B) a basin.

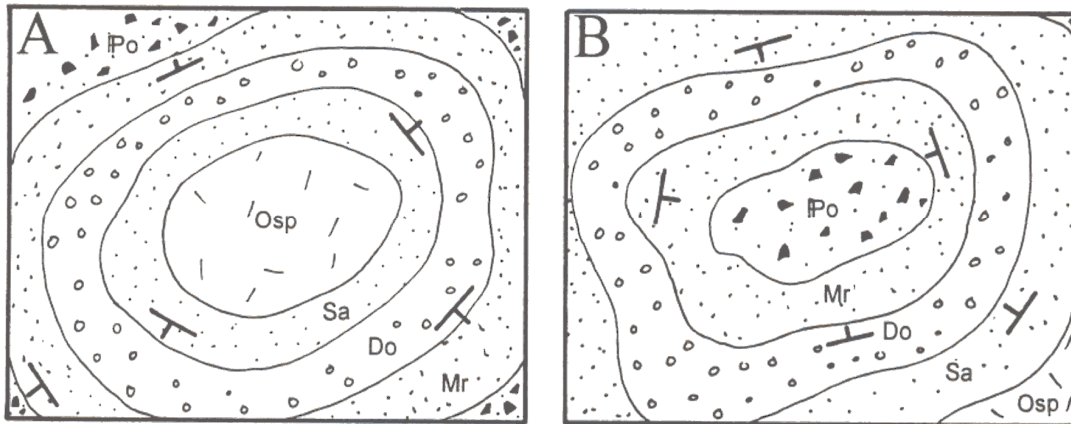
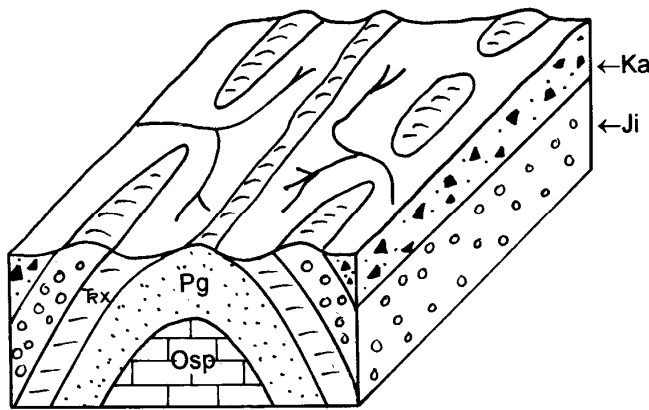
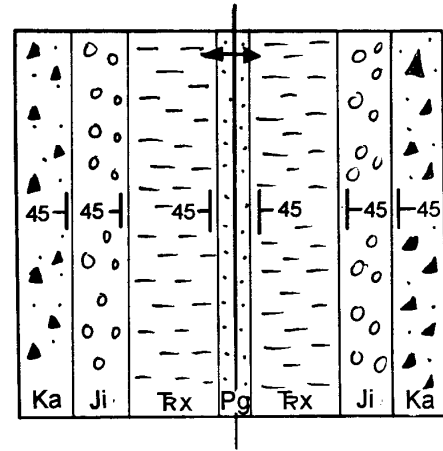


Figure 6.11: Effects of erosion on an anticline (A) and a syncline (B). Some layers are more resistant than others resulting in ridges and valleys. The insets show the pattern of repeated bedding that would be found on map views of these structures.

A) Anticline

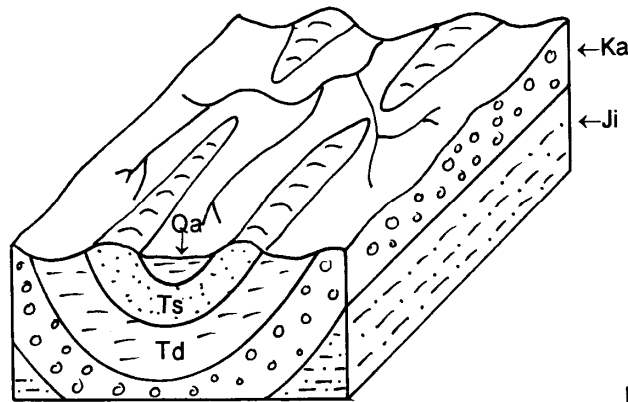


Oblique View

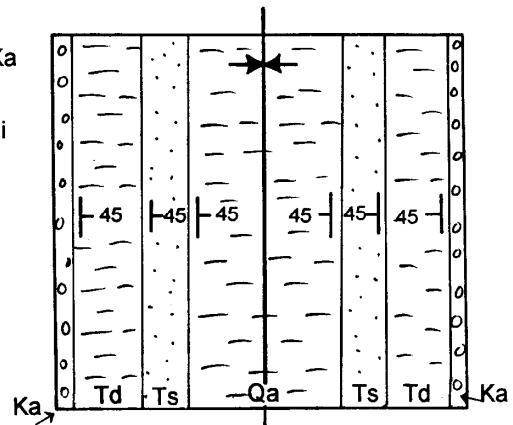


Geological Map (no scale implied)

B) Syncline



Oblique View



Geological Map (no scale implied)

6.5 Complex Fold Structures

If you can identify a single fold structure and properly label it (strike and dip of both fold limbs, fold axis etc.), you can probably handle the more complex situations discussed in this section. The main thing is to AVOID PANIC. Consider the example

presented in Figure 6.12. It looks pretty nasty doesn't it? The first thing that you need to do is to identify the main structures from the information available on the surface of the block diagram. The age data tells you which parts of the strata are the oldest and which are youngest. Careful examination of the example will reveal that there are two patterns of repetition. One repeats in the following fashion: Su, Do, Ma, Do, Su. The other repeats as follows: Su, Osp, C₁, Osp, Su. The first repeats around Ma which is the youngest layer in the sequence. This defines a syncline. The second repeats around the oldest bed (C₁) indicating an anticline. Once you identify all of the structures, add the relevant fold axis to the block diagram (Figure 6.13a). There really isn't much more information that you can use here to better refine your interpretation, so the best that you can do is to sketch in approximate orientations of bedding in the vertical faces of the block diagram and add strike and dip symbols on the upper (planar) surface (Figure 6.13b). Sometimes you will get much more information than this. There may be strike and dip symbols already on the block diagram and/or there may be a river crossing geological contacts (don't forget the Law of the "V"s from Chapter 5!). You will be given several other examples in class by which to refine your interpretive geological mapping skills. There are also several do-it-yourself cutout block diagrams in the optional exercises section of this chapter. They may help you if you are having problems visualizing some of the structures.

Figure 6.12: Schematic block diagram of a syncline-anticline pair.

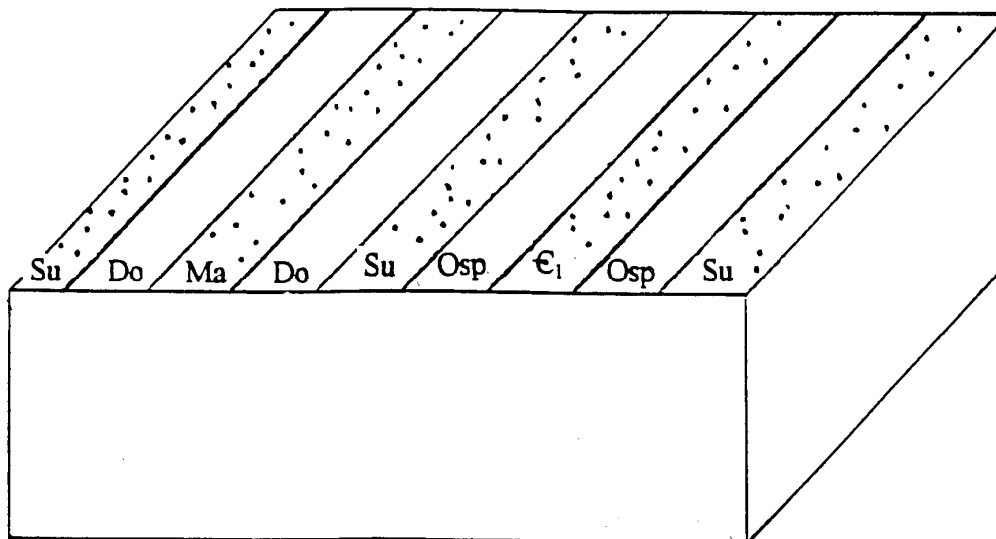
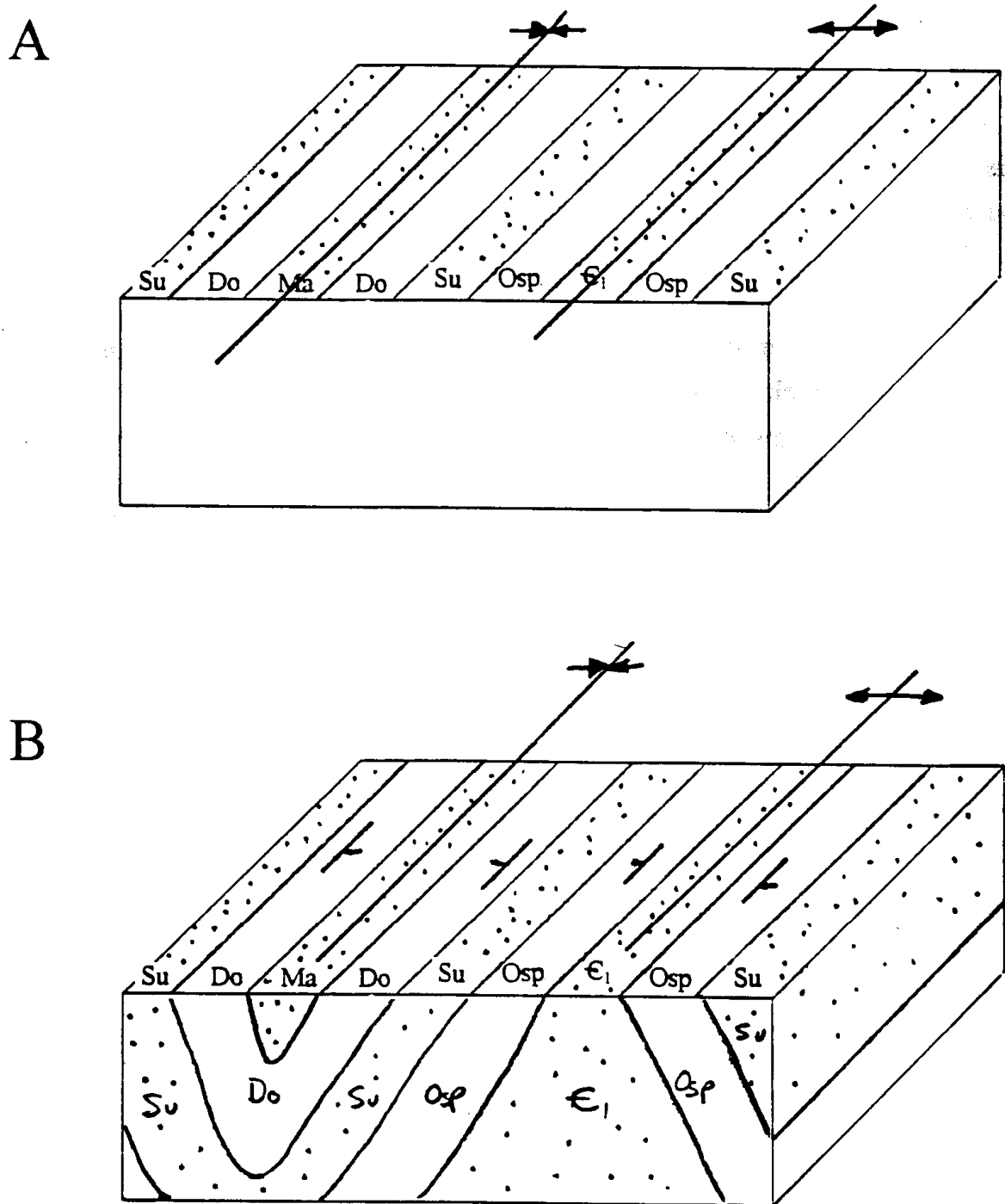


Figure 6.13: The same schematic block diagram of a syncline-anticline pair as shown in Figure 6.12 with added fold axes (A) and interpreted cross-section (B).

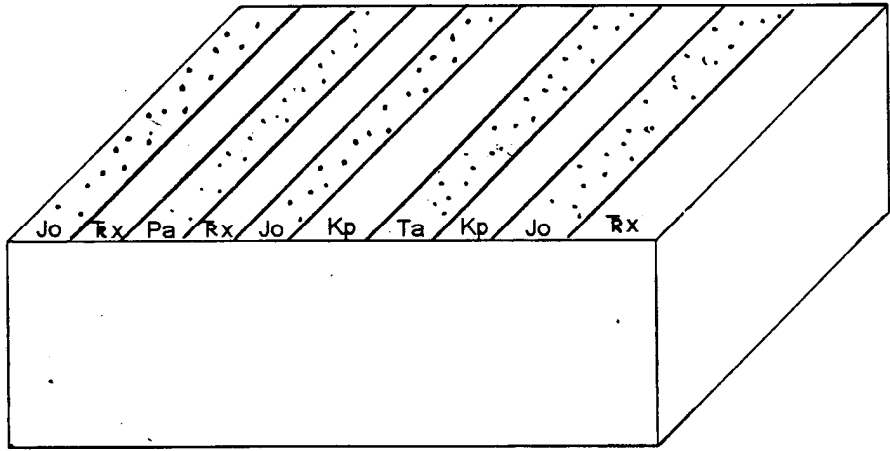


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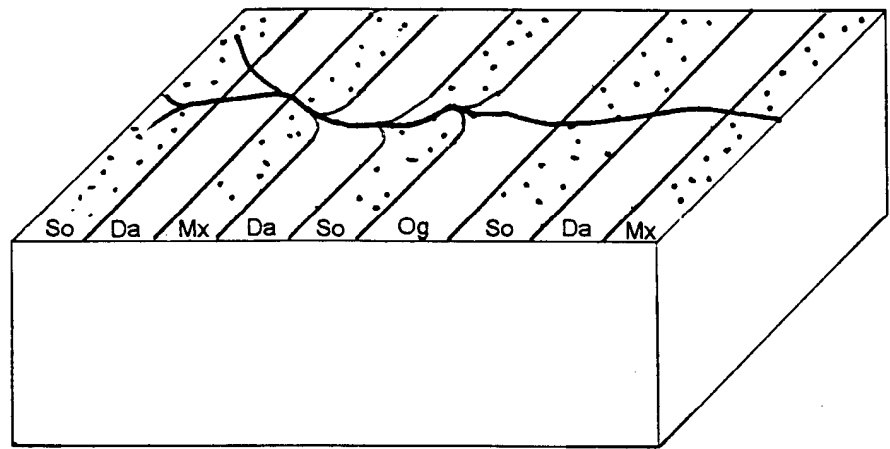
6.6 Exercises

1) Complete the following block diagrams of various fold structures and combinations of fold structures. For completeness, be sure to add ALL relevant geological mapping symbols to the horizontal surface of each block diagram (e.g., strike and dip symbols, fold axes, plunge direction etc.). Also remember to Obey the Law of the "V"s. (10 points each; total 60 points)

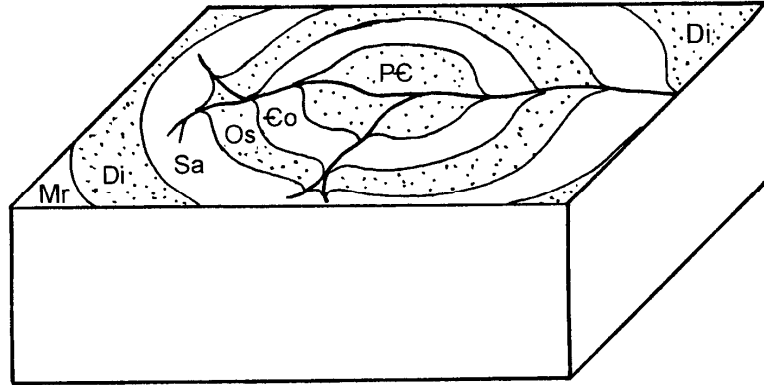
A)



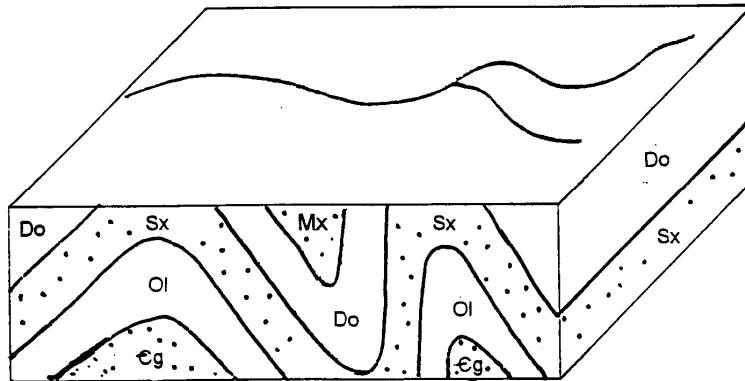
B)



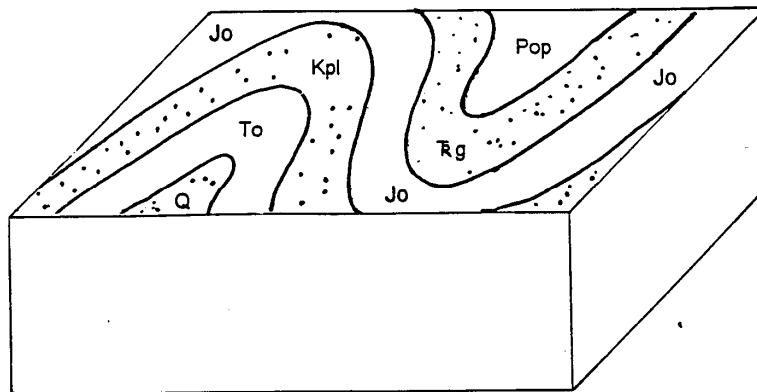
C)



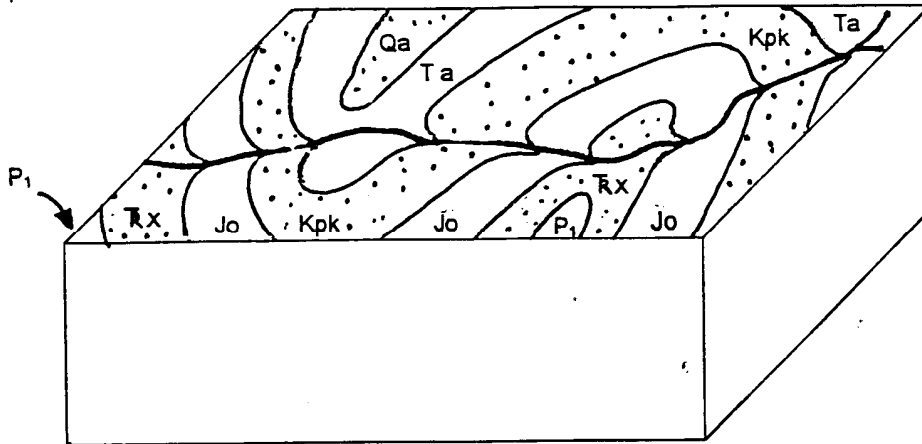
D)



E)



F)



Name _____

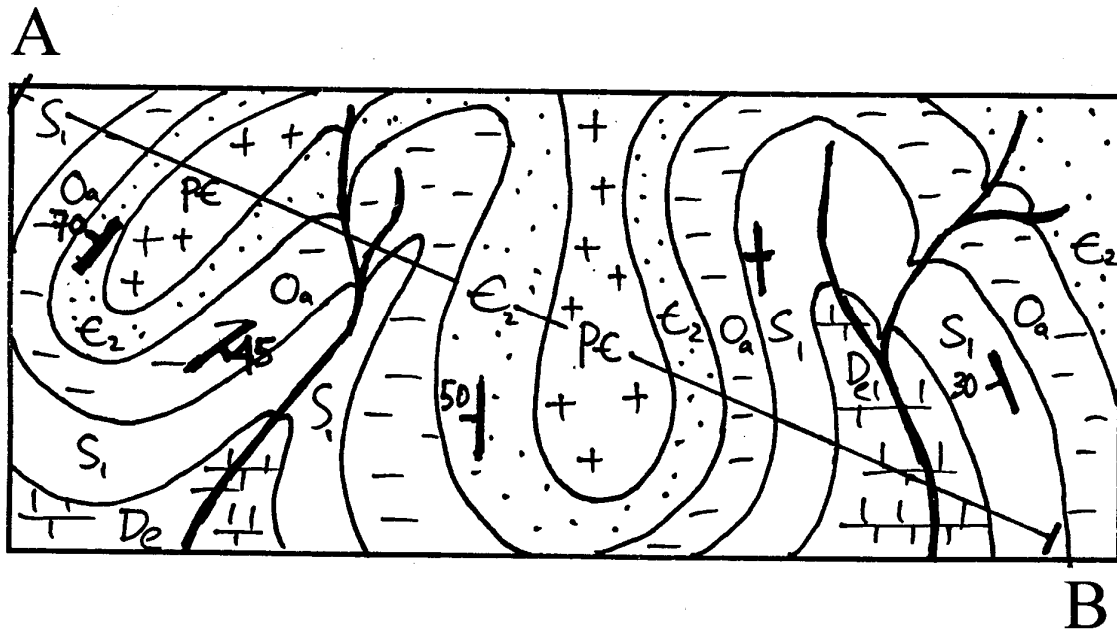
Optional Exercises

A) Past Lab Test: Want to know what to expect for the lab final in this class? This is a page from one of Dr. Haywick's exams a few years ago. Note: There are no faults on this map, the complexity is due entirely to folding [30 points]

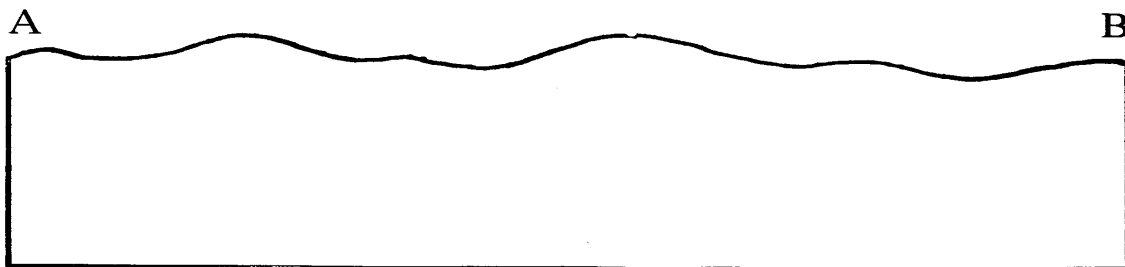
1) Draw all relevant fold axes on the map. Indicate the direction of plunge where necessary [5 points]

2) Draw a geological cross-section along the line A-B in the geological map below. Be sure to properly label the rock units in your cross section [20 points]

GEOLOGICAL MAP

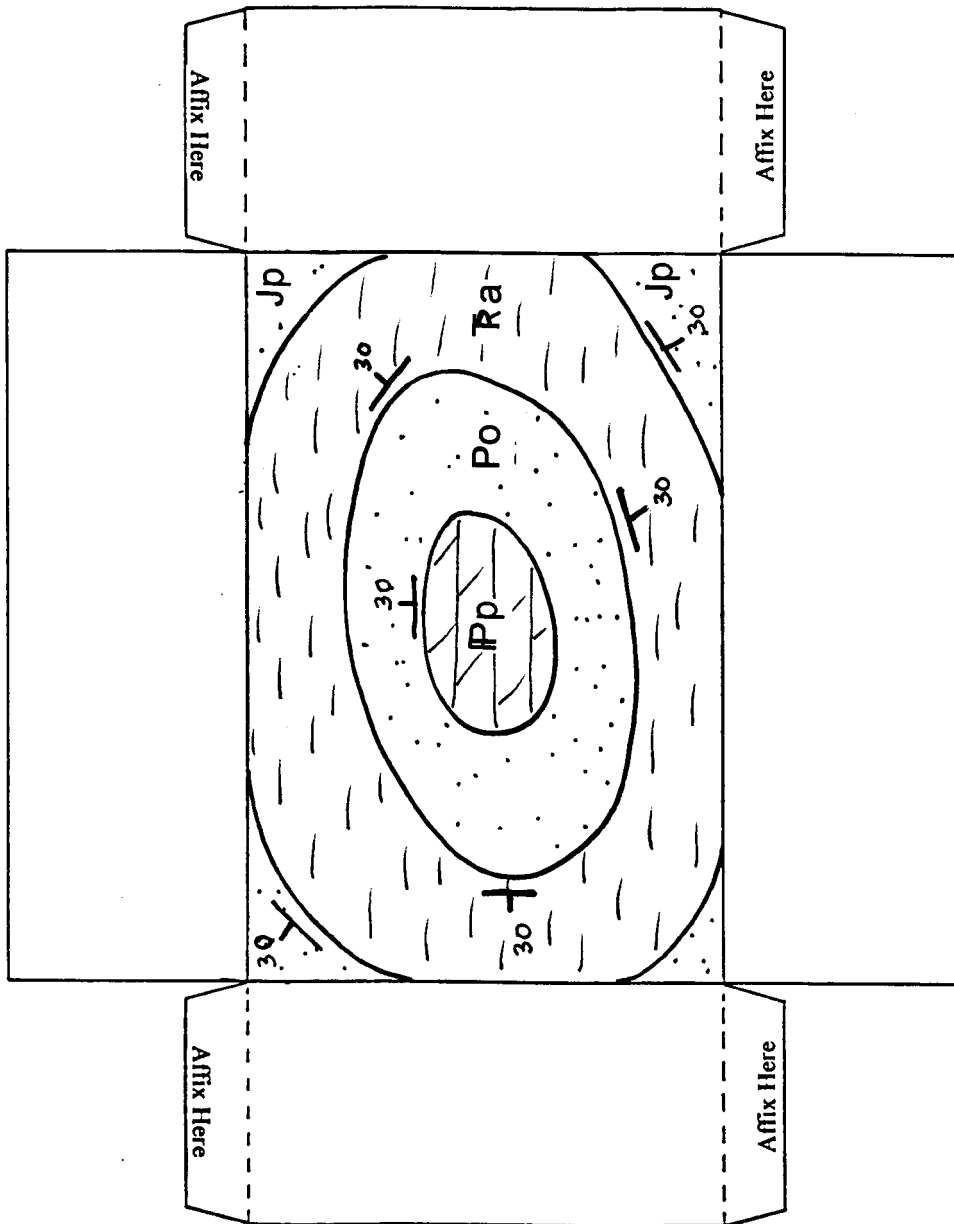


GEOLOGICAL CROSS-SECTION

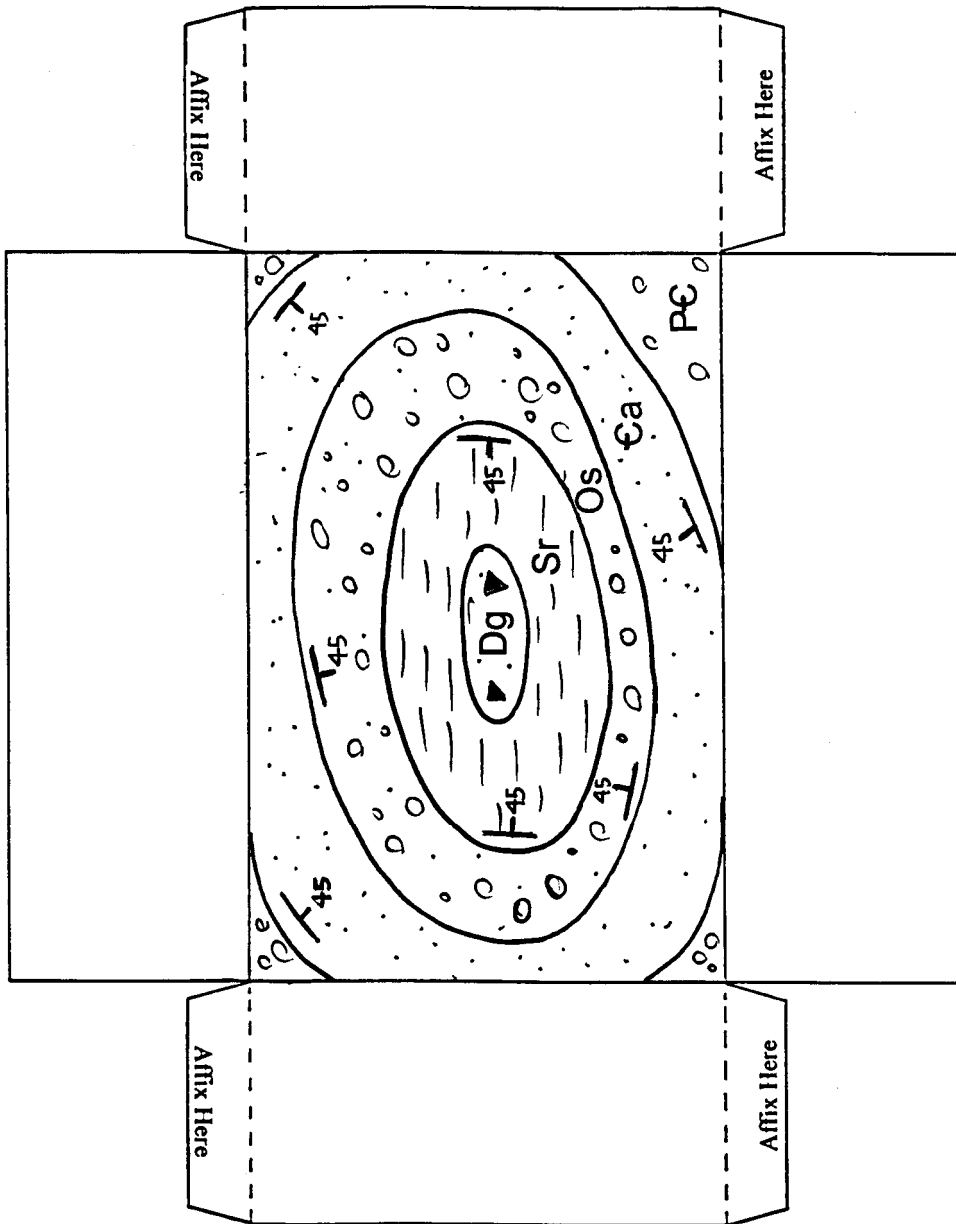


B) Cut out fold structures. Are you having problems visualizing some of the fold structures that we have been discussing in this section of the lab? If so, these do-it-yourself block structures may help you. Cut them out and then try to complete all sides. When you are done, color them in and tape or glue them together using the tabs that are indicated. You may first wish to photocopy them onto cardboard or heavy stock photocopy paper as those materials retain their shapes better.

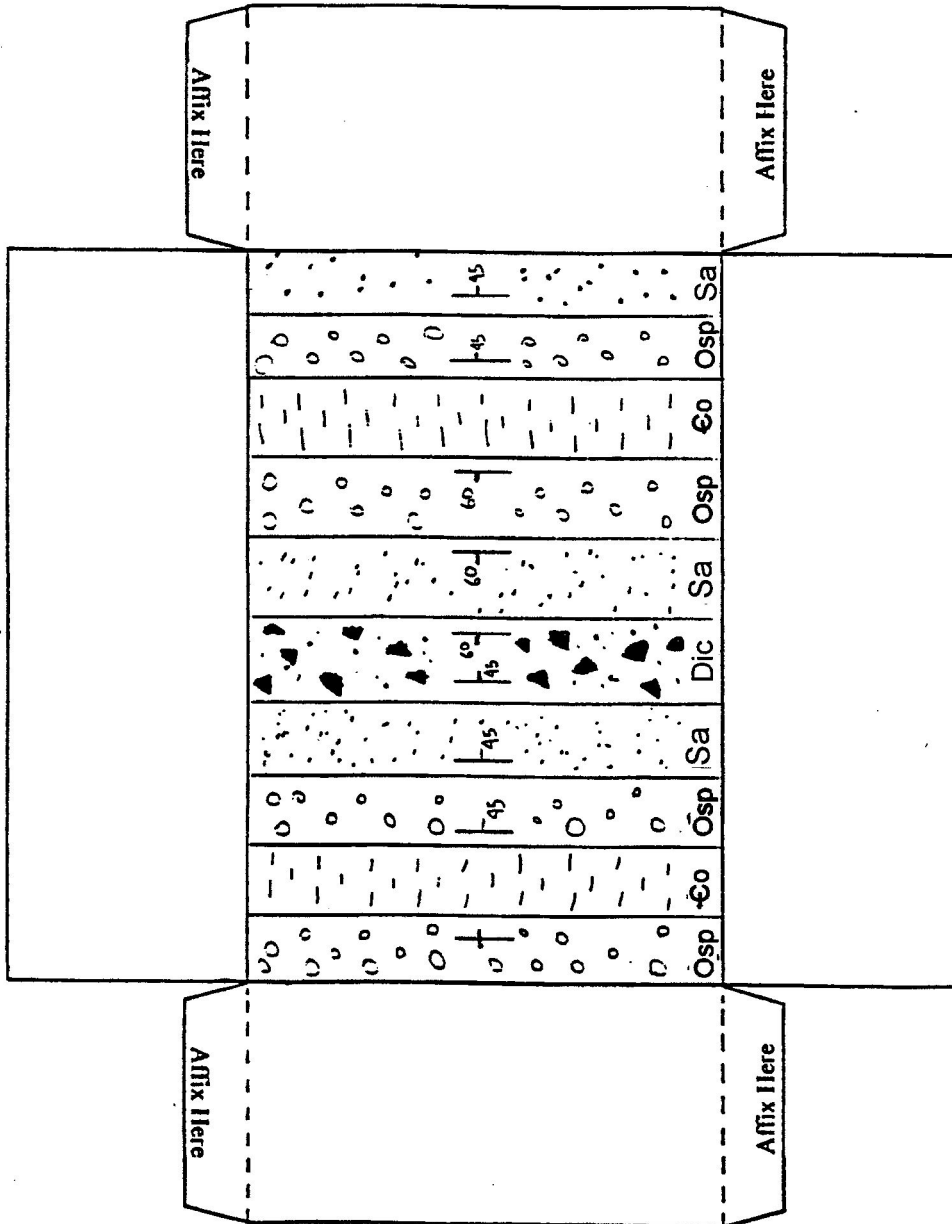
1) Dome



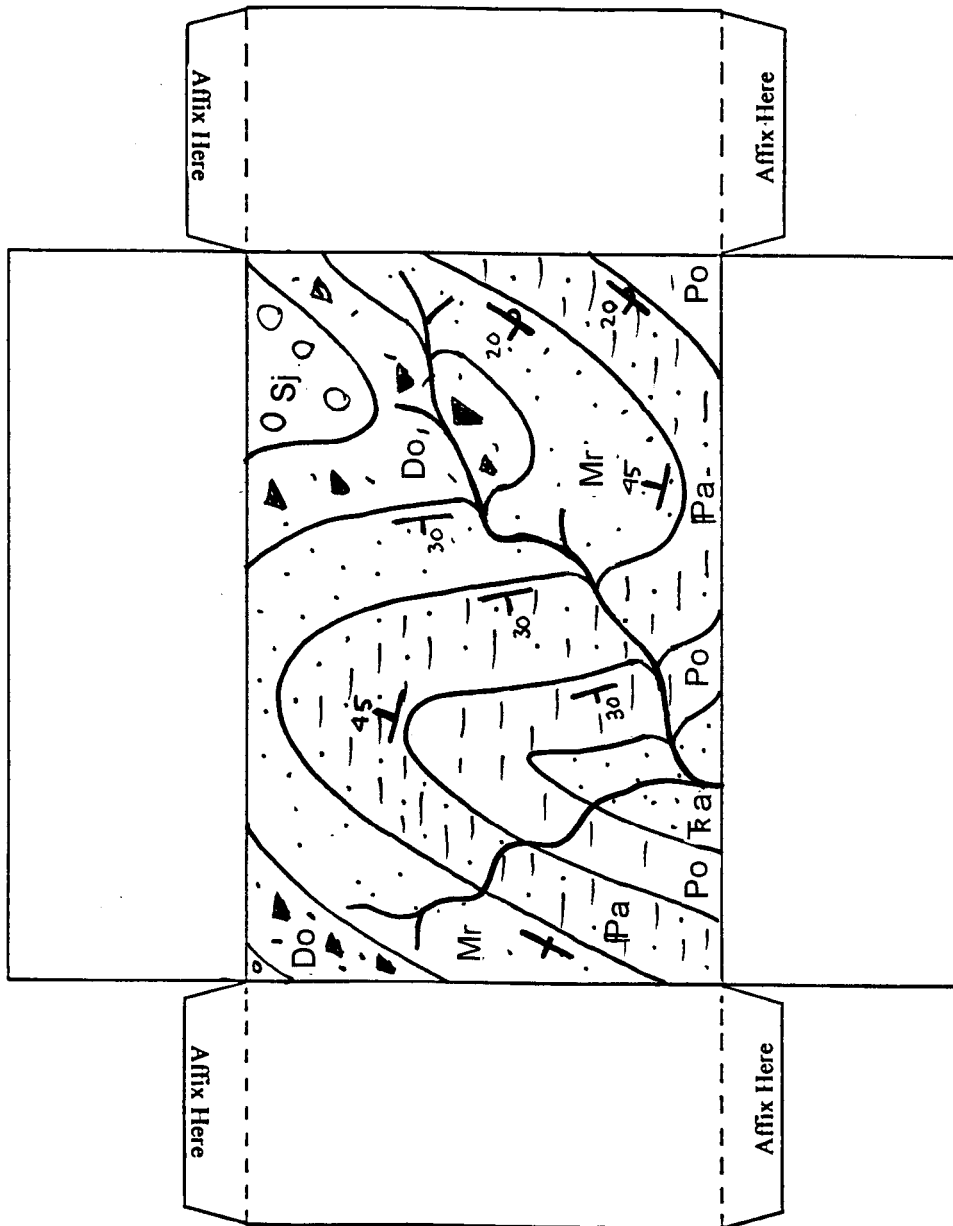
B) Basin



C) Complex horizontally-orientated folds



D) Plunging folds



Notes

