

Chapter 7

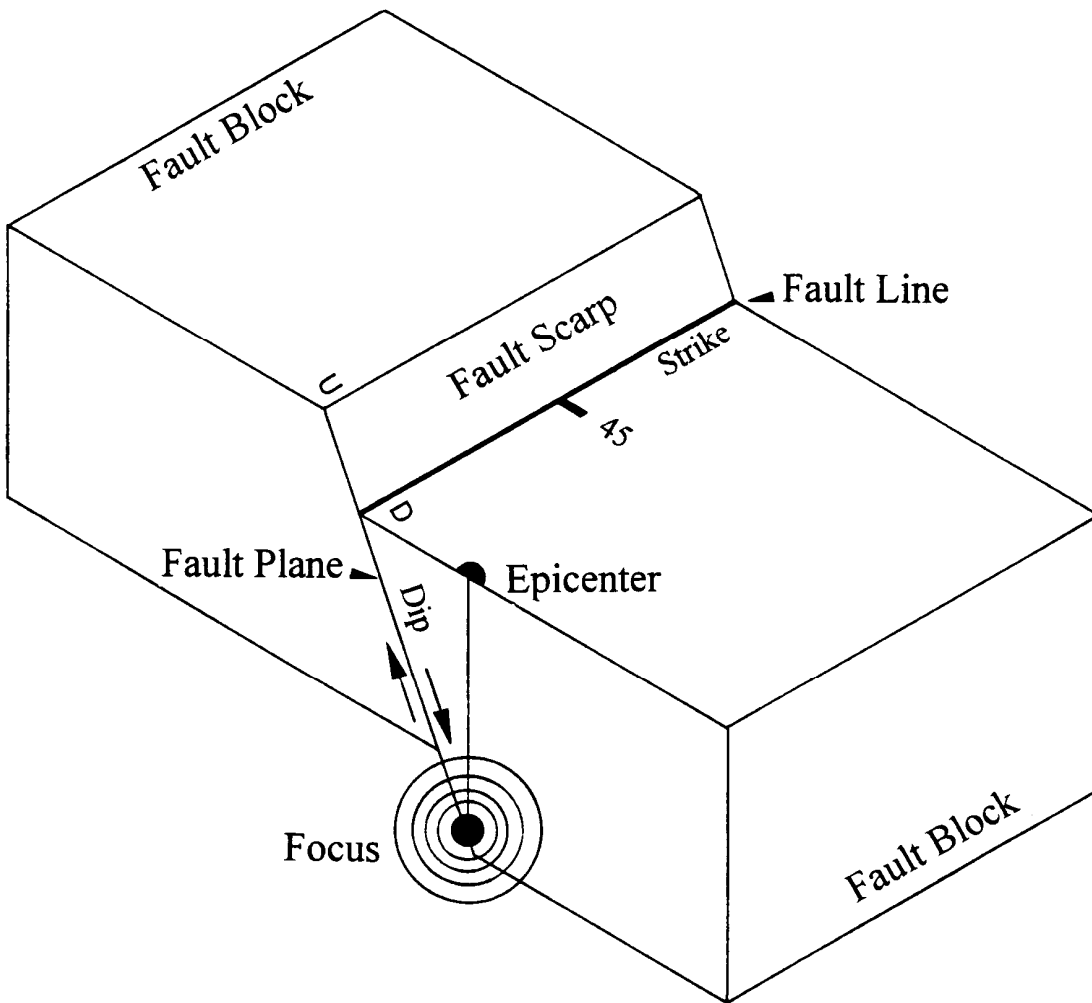
Geological Maps 3: Faulted Strata

Brittle deformation in rocks is characterized by fractures, joints and faults. Fractures and joints can be of any size, orientation or pattern. Some joints form regular patterns in rocks that are large enough to be seen in aerial or satellite photographs (e.g., rectangular joint patterns in granite bedrock of the Canadian Shield). However, as far as geological maps are concerned, most joints and fractures are minor "players" and can be ignored. Faults are another matter as they strongly influence geological maps. A **fault** can be defined as *any brittle deformation-induced fracture where there has been movement of the blocks on either side of the plane defining the fault (the **fault plane**)*. Fault nomenclature can be rather cumbersome. The fault plane is the actual surface where the strata has been broken (Figure 7.1). The **fault line** is the line made by the intersection of the fault plane and the surface of the Earth (Figure 7.1). The **fault blocks** are the strata on either side of the fault plane and the **fault scarp** is the cliff formed on the "uplifted" fault block where the fault plane rises above the surface of the Earth (Figure 7.1).

Faults are among the most studied of the geological features on the planet because they are where earthquakes occur. Earthquakes kill more people than any other natural

Figure 7.1: Schematic diagram illustrating key components of fault-systems. The fault illustrated is of a normal dip-slip variety.

Figure shows a cross-section across a grabben-horst-graben triplet. The dashed lines show the pre-erosion level of the fault blocks. From: LeConte, J., 1905. Elements of Geology. D. Appleton and Co., New York, NY, 667p.



process with the possible exception of hurricanes. As a matter of record, 1999 was a terrible year for earthquakes. Tens of thousands of people were killed in only three earthquakes (two in Turkey; one in Taiwan). Earthquakes occur due to the build-up of stress past the point of natural resistance (friction) of rock strata. The stress can be compression, tension or shear. All will produce earthquakes, but as you will see shortly, each of these forces produces different types of faults.

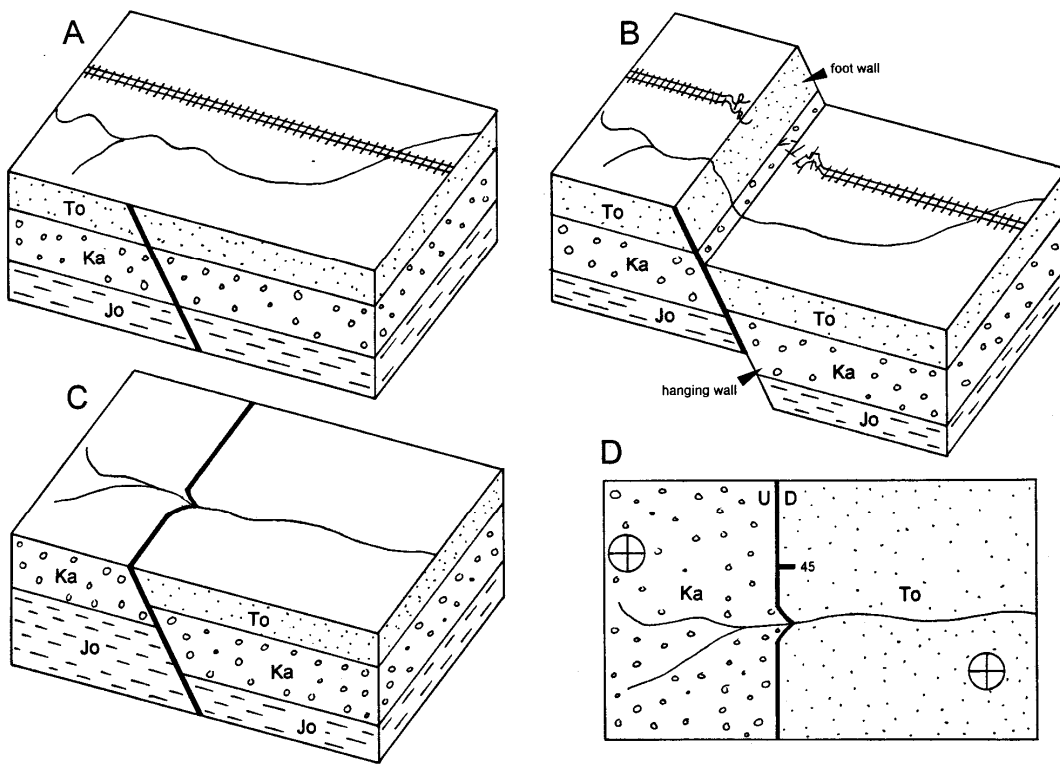
Stress tends to build up slowly, but steadily in rocks. Sometimes there will be **precursor** evidence of an impending earthquake (soil creep, surface tilting, increase in emission of subterranean gases). More often than not however, the ground just starts shaking. The point on the fault plane where the slippage occurs is the point where all

seismic waves are emitted. This is called the earthquake **focus** (Figure 7.1). The seismic waves travel exceptionally fast (4 to 7 km/second) in all directions from the focal point including straight up. The point on the Earth's surface directly above the focus is the point where the seismic waves are the strongest and the shaking is the greatest. This is called the **epicenter** (Figure 7.1). The intensity of an earthquake is directly proportional to the amount of stress released and inversely proportional to the depth of the focus. The absolute worst thing that can happen to a city is to be situated atop a fault line and then to have a shallow earthquake along the fault plane (e.g., focus less than 50 km deep) that releases a tremendous amount of energy. This is exactly what happened beneath Turkey and Taiwan in 1999, Kobe, Japan in 1995 and Alaska in 1963. All of these examples, and most of the world's most powerful earthquakes, have occurred due to compression along convergent plate boundaries. The type of fault that occurs here and in other regions where compressive stress occurs is unique and quite different from those that result through tension and shear. Ultimately, you should be able to determine the type of force responsible for a fault by figuring out the type of fault that it is. Chapter 6 introduced you to folds and if you were able to identify specific types of folds on geological maps, then you should be okay with the faults. The only new complication is that fault planes can be orientated at any direction (strike) and be inclined at any amount (dip). Exercise care when interpreting the geological maps and perspective diagrams that we have provided to you as examples and for the exercises.

7.1 Stress and Faults

Each type of stress (tension, compression or shear) produces a specific type of fault. Tension and compression tend to produce faults where movement is in the direction of the dip component of the fault plane. This type of fault is called a **dip slip fault**. There are two broad types of dip slip fault that are distinguished on the basis of the direction of slip. Tension will produce movement where one block slips *downward* compared to the other as demonstrated in Figure 7.2. This is called a **normal dip slip fault** or **normal fault** for short). It is important to realize that the absolute motion of the two blocks may not be determinable on the basis of a single perspective diagram. Only the *relative* motion can be determined. Tension tends to stretch rocks, so the net result of normal faulting is extension. Compression will produce movement along a fault plane where one fault block moves *upward* compared to the other (Figure 7.3). This movement is the

Figure 7.2: Perspective diagrams of a normal fault produced following release of tensile stress. The pre-faulting situation is illustrated in (A). Note that the underlying strata is horizontally bedded and obeys the Law of Superposition. After slippage, one fault block moves *downward* relative to the other resulting in a stretching of the strata (B). The relative position of the hanging wall and footwall (as discussed in GY 111 lectures) is also indicated on the diagram. Erosion tends to remove strata from the topographically higher fault block (C). Notice the "V" produced where the stream crosses the fault plane. A geological map showing all necessary symbols is illustrated in (D). U and D refer to relative up and down motion of the fault blocks.

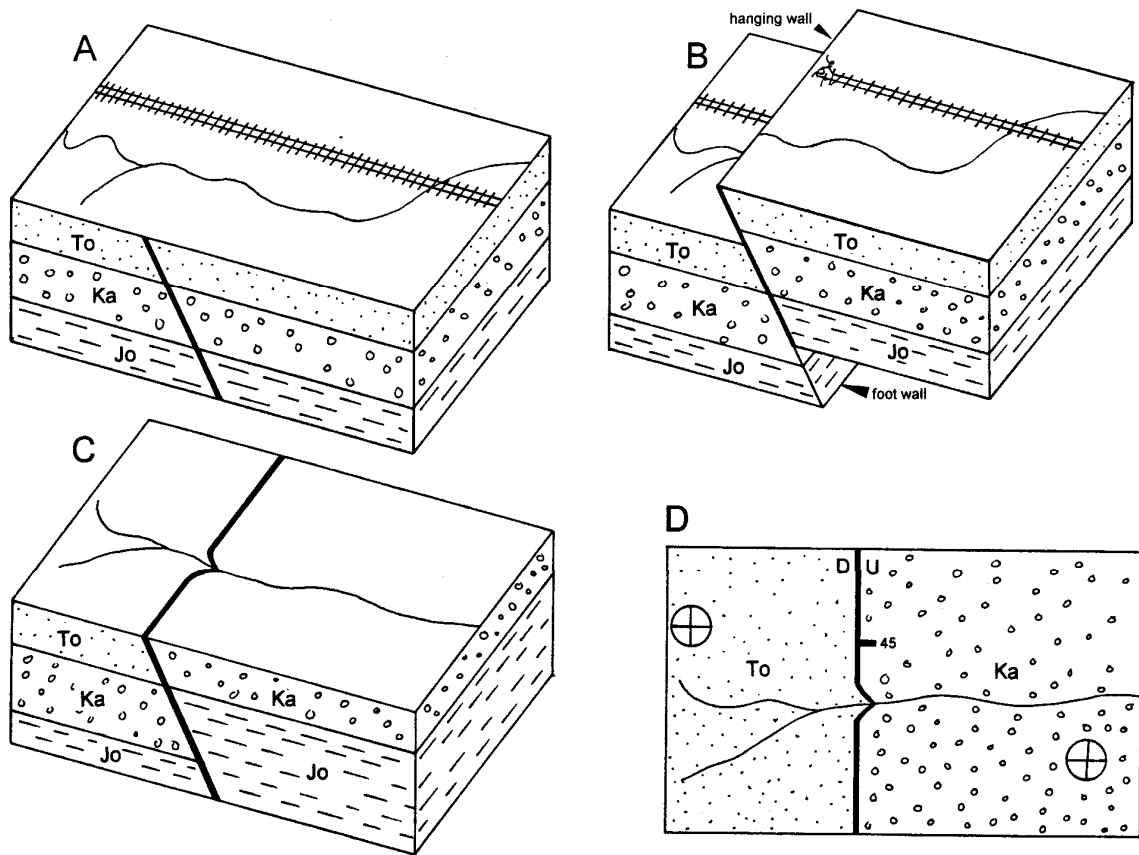


opposite or reverse to that seen in normal faults which is the reason why they are called **reverse dip slip faults (reverse faults)**.

Shear stress produces faults where movement occurs in the strike direction of the fault plane. These faults are called **strike slip faults** and as with dip slip faults, there are two varieties depending upon the direction of slippage. Strike slip motion is a bit trickier to describe than dip slip motion. What you have to do is picture yourself standing on one fault block and looking toward the fault line. If objects on the opposite side of the

fault appear to have been translated to the left, that fault would be considered a **left lateral**

Figure 7.3: Perspective diagrams of a reverse fault produced following release of compressive stress. Descriptions for individual diagrams are the same as in Figure 7.3. Note the differences in terms of sense of motion, erosion of strata and geological mapping symbols.

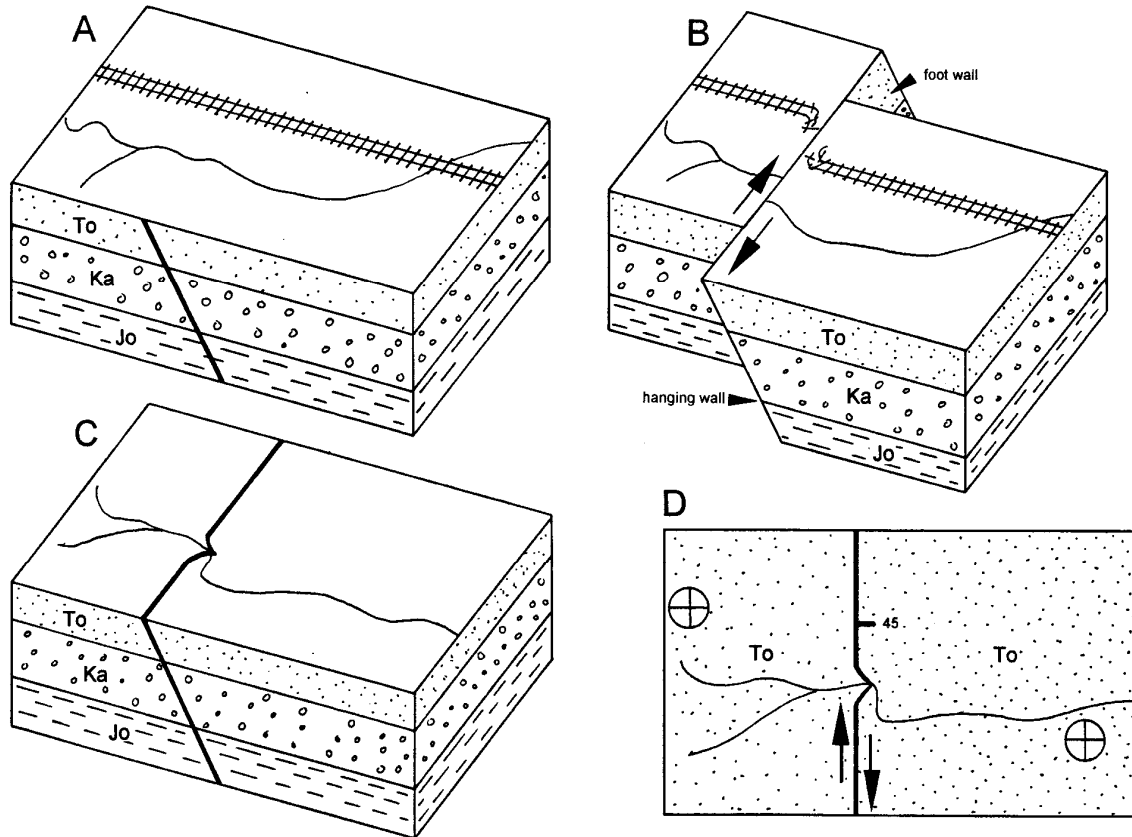


strike slip fault. If objects appear to have shifted to the right (as in Figure 7.4), the fault is considered to be a **right lateral strike slip fault**. Incidentally, it doesn't matter which fault block you "stand" on. The motion is always either to the left or to the right.

There are also faults where there is a combination of strike slip and dip slip motion (e.g., Figure 7.5). These faults are called **oblique slip faults**. At this level (GY 111), it is not necessary to distinguish between oblique slip faults that have normal/reverse dip slip motion and/or left/right lateral strike slip motion (although you can try if you want

to!). All you have to do is determine that there is a combination of the two senses of motion; dip slip and strike slip.

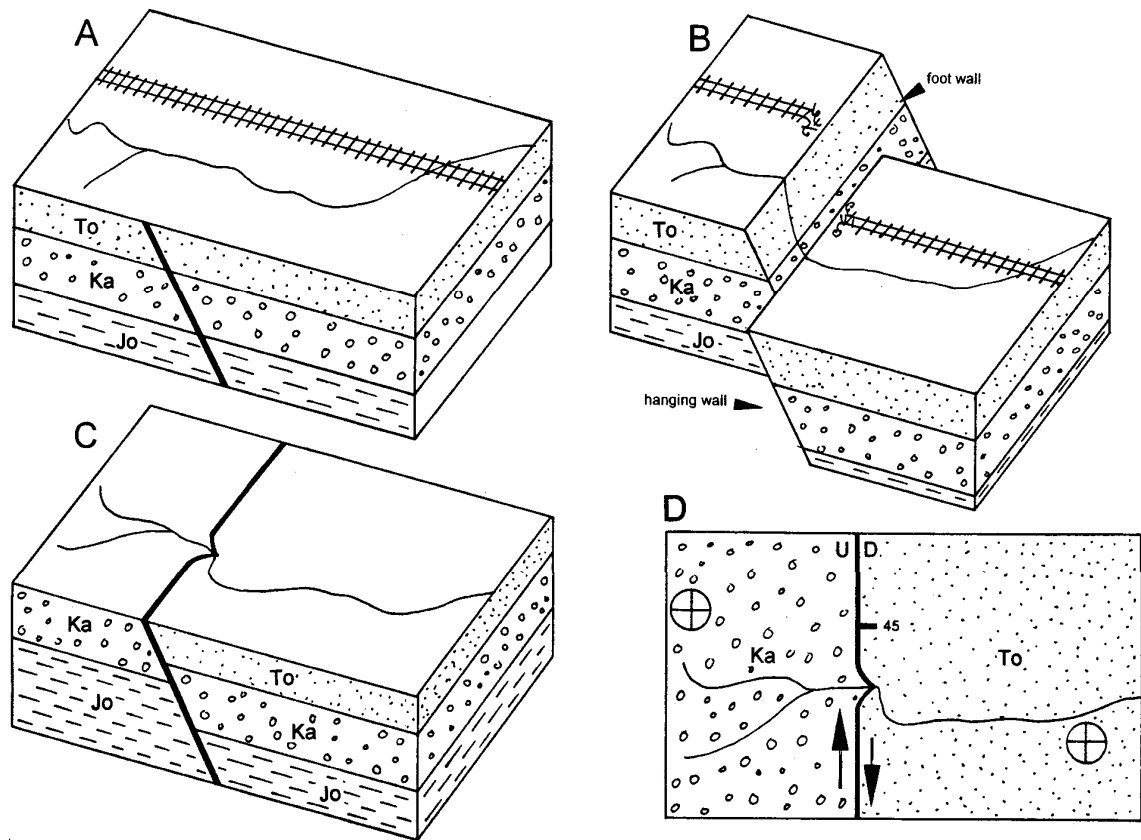
Figure 7.4: More of the same, but this time for a right-lateral strike slip fault produced following release of shear stress.



The last type of fault is actually a variety of reverse faults. In mountain belts formed through compression (which is most of them), reverse faults with variable dip can form. They may start off at depth with a steep dip ($>60^\circ$) and then shallow dramatically as they approach the surface of the Earth ($<5^\circ$; Figure 7.6). They are sometimes called **low angle reverse faults**, but they are more typically referred to as **thrust faults**. As you will see in the mountain building section of the GY 111 lectures, thrust faults form large components of most mountain belts, including much of the Front Ranges of the Rocky Mountains. The neat thing about thrust faults is that they can produce numerous repetitions of strata. Thrust faults also tend to "piggy-back" on top of one another resulting in significant shortening of sedimentary successions. The Front Ranges of the

Rocky Mountains for example, have been reduced in the horizontal dimension by more than 60 km (60 km of shortening). Much of this mass was pushed up into the sky (here there be mountains).

Figure 7.5: One more time. Perspective diagrams of an oblique fault produced following release of tensional and shear stress. Note that in Figure 7.5d, arrows and U/D symbols are used to indicate relative motion.

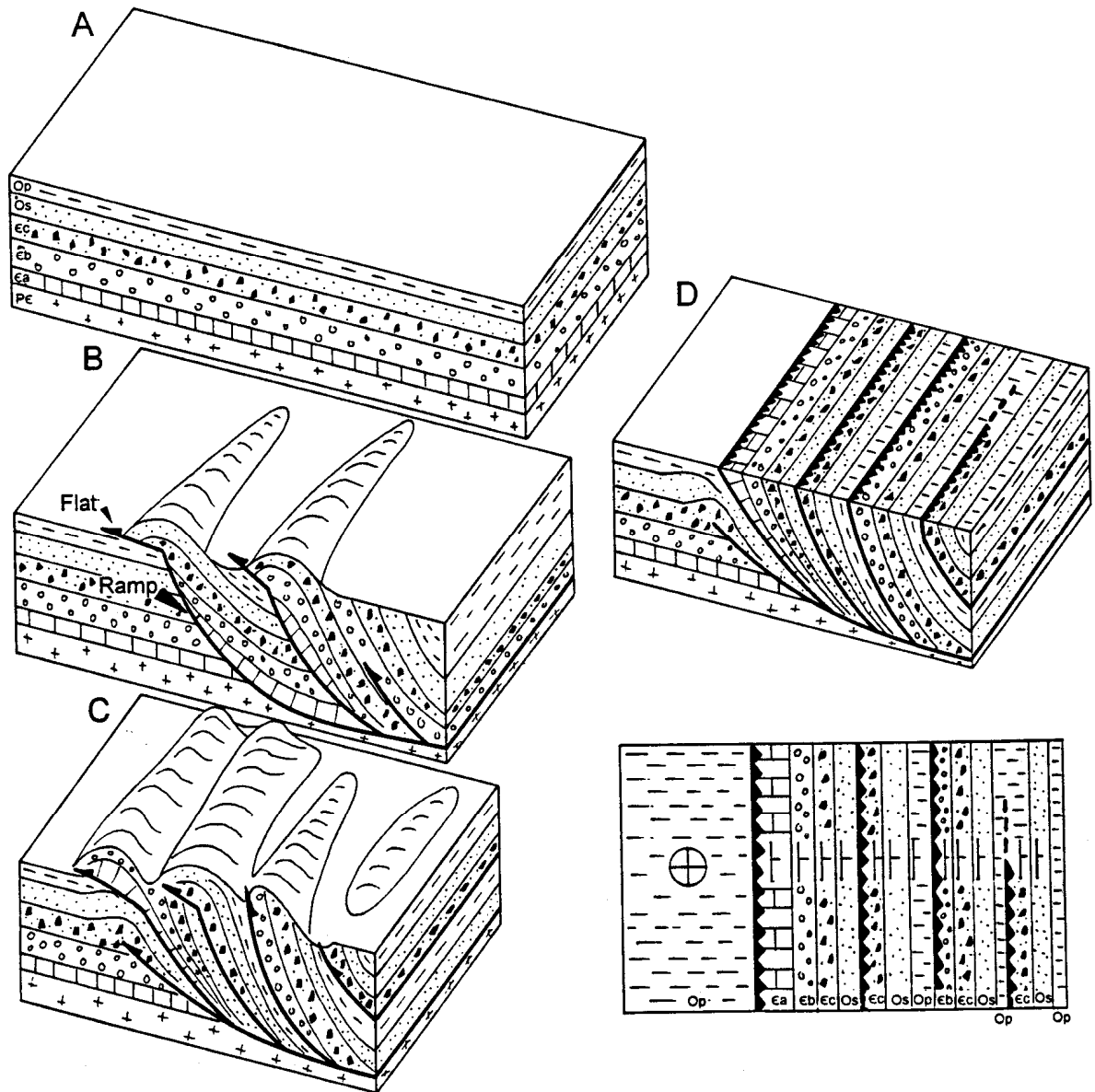


7.3 Faults on Block Diagrams

Okay, let's be honest. If you did not like dealing with folds on perspective diagrams, you are really going to despise having to interpret faults in this manner. The problem is that the fault plane can be orientated in any direction and dip by any amount. Sound familiar? This is the same variability demonstrated by inclined planes and in fact, fault planes are treated exactly the same way as any type of plane in geology. That means you can describe them using strike and dip. Instead of adding a separate strike and dip symbol to faults on geological maps, it is conventional just to add a dip indicator

directly on the fault line (see Figures 7.3d - 7.7d). Faults are also usually drawn in **bold** line format to distinguish them from stratigraphic (bedding) contacts. You must also specify the

Figure 7.6: Evolution of thrust faults. This variety of reverse fault is typically found in mountain belts that have been "shortened" through compressive shear. (A) Pre-compression. (B) Initial faulting. Successive thrust faults usually propagate from the base of others. Note the presence of both flat and ramp components. (C) Thrusting eventually leads to linear mountain belts. (D) After erosion, it can be seen that the faults are often stacked up producing many repetitions of the underlying strata. Thrust faults usually dip in the same direction, but the amount of inclination of the fault plane can vary greatly (even within a single fault). (E) a geological map showing all necessary information concerning structure.



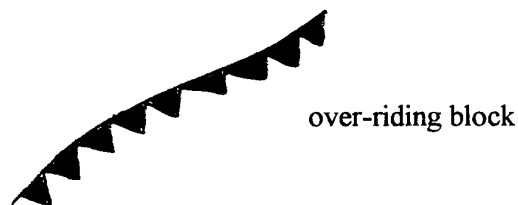
direction of movement between the two fault blocks. For normal and reverse faults, you must indicate which block has moved "up" and which block has moved "down" *relative to each other*. On geological maps, the letters **U** and **D** are added to the fault blocks on either side of the fault line. In a normal fault, the block down dip of the fault line moves down (**D**) relative to the opposite block (Figure 7.3d). In a reverse fault, the block down dip of the fault line moves up (**U**) relative to the opposite block (Figure 7.4d).

You should be able to distinguish the type of fault by sorting out the direction of motion (this is one of your major goals for this chapter). This particular task is not all that difficult, but it does take a bit of patience and you have to learn how erosion modifies maps. As with erosion on folded strata, a lot of change can occur to areas that are topographically higher than others. The best advice is don't rush your interpretation.

Fault blocks that have been uplifted relative to others will tend to be eroded faster. As a result, lower strata is exposed in uplifted fault blocks. Unless the strata is overturned, the lower you go, the older the strata gets. So the best way to determine relative motion along a fault is to sort out the age relationships of the fault blocks. If you examine Figures 7.3 and 7.4 you will see that the "uplifted" blocks are both underlain by older strata. For simplicity, both cases involve horizontal bedding (the easiest scenario), but even if the situation were more complicated (inclined bedding or folded strata), the age relationships would hold.

Strike slip motion is indicated on maps by using opposed arrows that show the relative direction of motion of each fault block (Figures 7.5 and 7.6). In simple left or right lateral strike slip faults, there may be no differential erosion because neither fault block has been uplifted relative to the other. If the strata is horizontally bedded, there will be no vertical displacement of strata. If things are more complex (e.g., strike slip motion cuts across a fold axis), displacement may be obvious. For a fold, the best sign of strike slip motion is a lateral shift in the fold axis. Oblique slip faults may show lateral displacement and juxtaposed older strata.

Reverse faults are indicated on geological maps by a specific symbol (below and Figure 7.7):

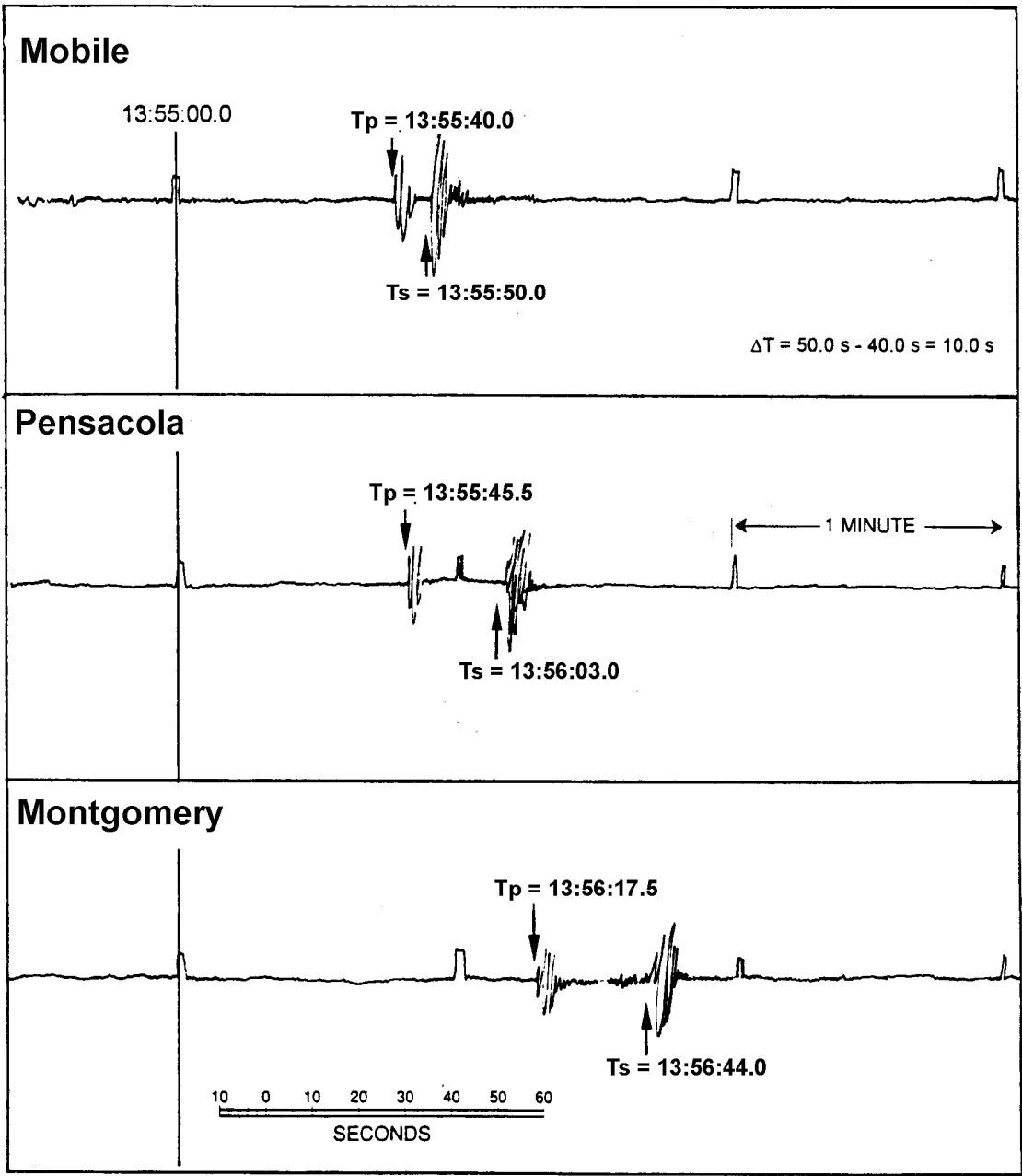


The triangular pattern points in the direction of the over-riding strata (see Figure 4.8). This is the only real symbol that you need to add to geological maps containing thrust faults.

7.4 Earthquakes and Faults

When the stress builds up along a fault plane passes the point of friction's ability to resist movement, something has got to give. Usually the "give" is sudden slippage. The point where this occurs is the focus of an **earthquake** or **tremblor**. Earthquakes can release tremendous amounts of energy in the form of seismic waves. Several types of waves are produced. **P-waves (primary waves)** pass through rocks more or less like a compressive pulse. The rocks are repeatedly compressed and stretched as the P-waves pass through them. **S-waves (secondary waves)** pass through rocks via shear. The importance of each of these waves (as well as **L-waves**) will be discussed in the lecture component of GY 111. As far as the lab goes, there is a fundamentally useful difference between P- and S-waves that we can use to determine when and where an earthquake has occurred. P-waves travel faster than S-waves. If you are near the epicenter of an earthquake, the two packages of waves more or less arrive simultaneously (or you would be too busy rolling all over the floor to notice any lag between them), but if you are a long way from the epicenter, there is a distinct separation between the arrival time of the P- and S-waves. It follows that the further away that a **seismograph** is from the epicenter of an earthquake, the more the separation between the two sets of waves. Seismographs record ground motion. When an earthquake occurs, even if it is a long way off, ground motion is measurable with seismographs that are enhanced with amplifiers. Figure 7.8 shows schematic **seismograms** for three locations following an "earthquake". Note that the arrival times for P- and S-waves differ at each of the three locations. So too does the separation between the two types of waves. The arrival time of the P-waves is designated as **T_p**. The arrival time of the S-waves is designated **T_s**. The difference between them (**T_s-T_p**) is designated as **ΔT** and it is measured in seconds. For the earthquake recorded by the fictitious seismograph at Mobile, ΔT measures 10.0 seconds. From this data, it is

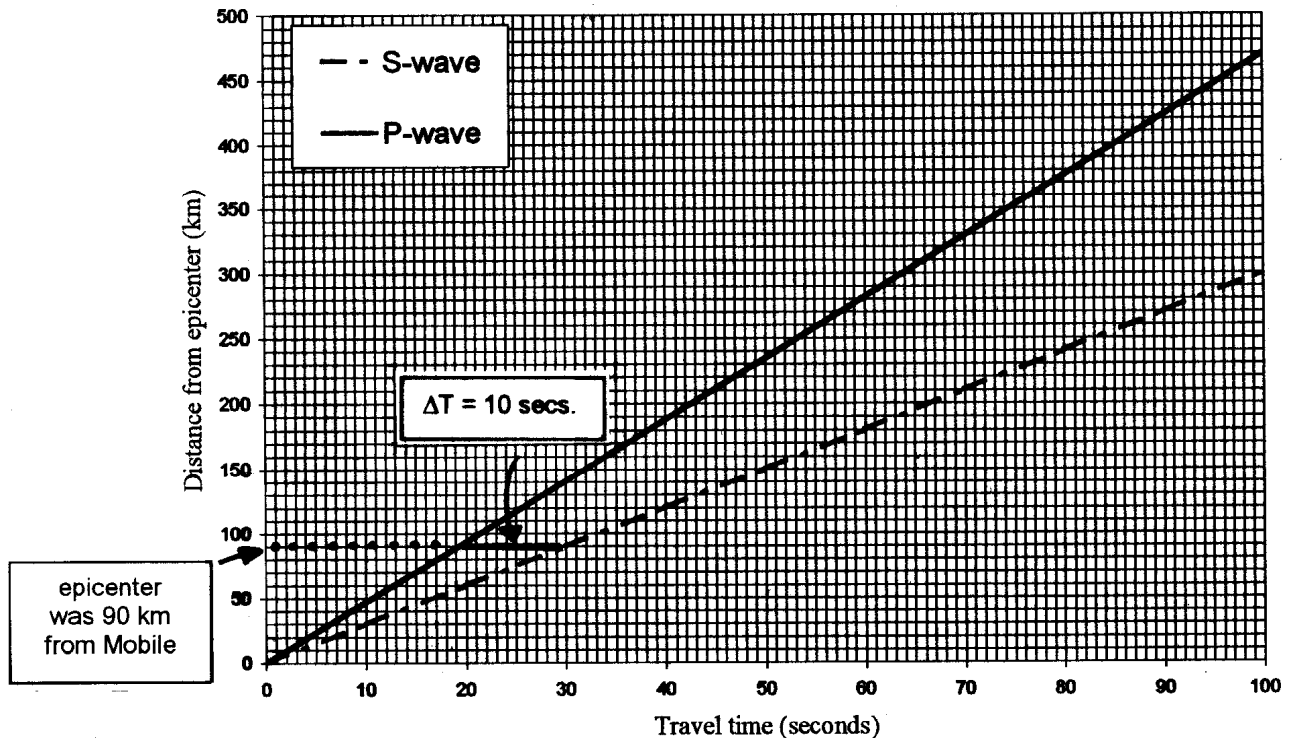
Figure 7-8: Schematic seismograms from three fictitious seismograph stations in the Gulf Coast region. Time clicks are indicated by periodic upward deflections in the trace. The first (13:55:00) is used to synchronize all three of the stations. Refer to the text for additional explanation of these diagrams.



possible to determine the distance between Mobile and the epicenter of the earthquake¹. Figure 7.9 is a graph that summarizes time versus distance traveled of P- and S-waves following an earthquake. The distance between the two lines is ΔT . If you use the time scale, you can find the one place on the chart where ΔT exactly equals 10.0 seconds. That corresponds to a distance of about 100 km, hence the earthquake epicenter had to be 100 km away from Mobile. Unfortunately you don't really know which direction the epicenter was from Mobile. You must therefore draw a circle with radius 100 km centered on Mobile. In order to pinpoint the exact location of the epicenter, you have to do the same procedure for each of the other two seismograph stations.

Figure 7.9: Simplified travel time curves for P- and S-waves through "average" rock. Example data is from Exercise 1a on the next page.

Seismic Wave Travel Time Curves



¹ Time on seismograms needs to be measured very accurately. **Time clicks** are added to each seismogram trace every minute and computers can measure the arrival time of P- and S-waves down to a fraction of a second. Time is designated in hours:minutes:seconds. So the time 13:55:50.0 represents 50.0 seconds after 1:55 P.M.

Name: _____

7.5 Exercises

1a) Determine the location of the earthquake epicenter using data summarized in Figure 7.8. Fill in the blanks on the following table before you get too carried away with the map (It will help you to piece together all of the information before you start drawing circles). **(Worth 12 points)**

Station	Ts-Tp	ΔT (seconds)	Epicentral Distance (km)
Mobile	13:55:50.0- 13:55:40.0	10.0	90
Pensacola			
Montgomery			

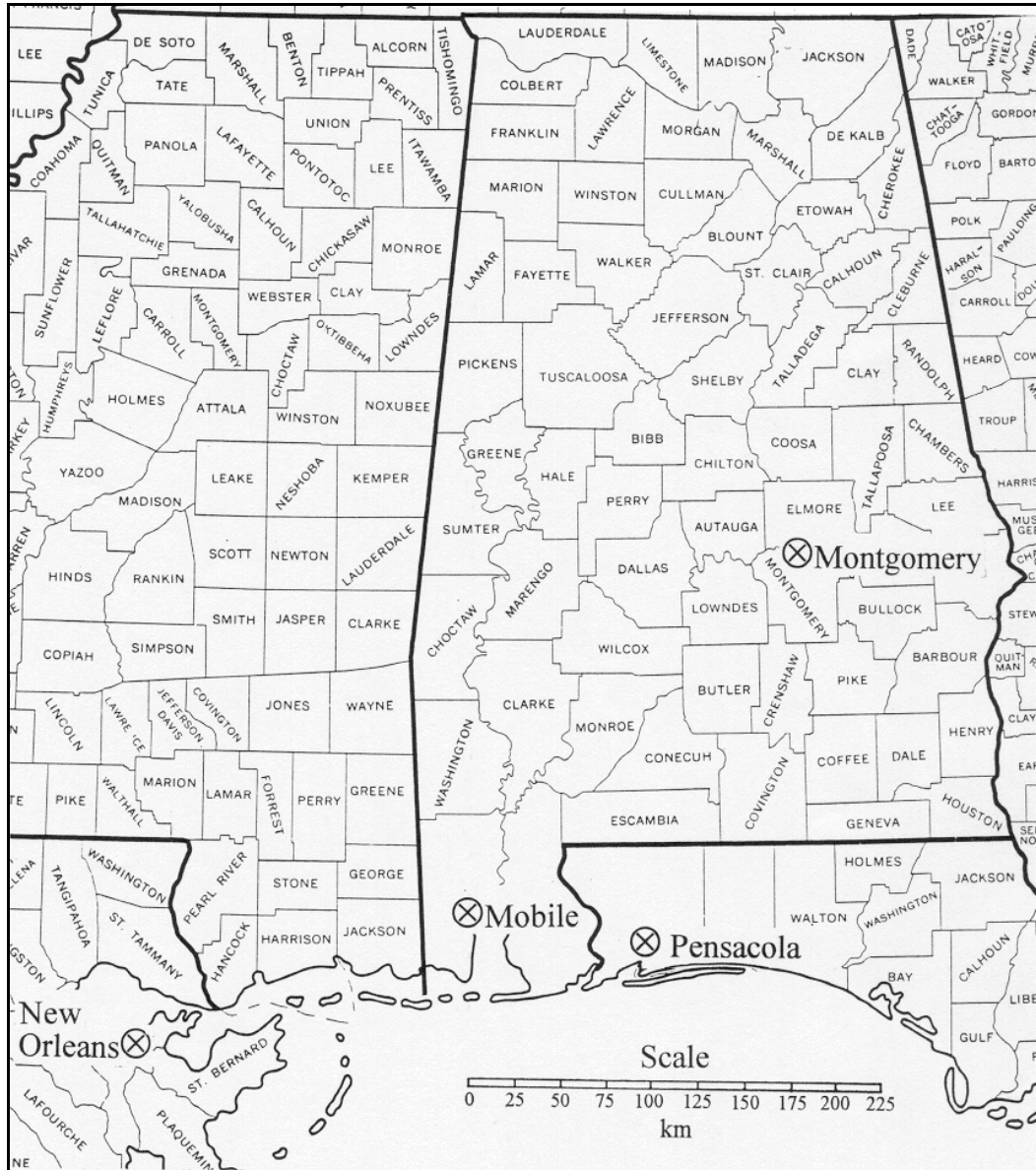
1b) Where was the epicenter of the earth quake? _____ **(1 point)**

1c) Now try working backwards. Once you know where the epicenter was located, you should be able to determine ΔT , Ts, Tp etc. for other seismograph stations. So let's try it for New Orleans. Assuming that Tp for the New Orleans station was 11:58:37.5, what would Ts have been?

_____ **(4 points)**

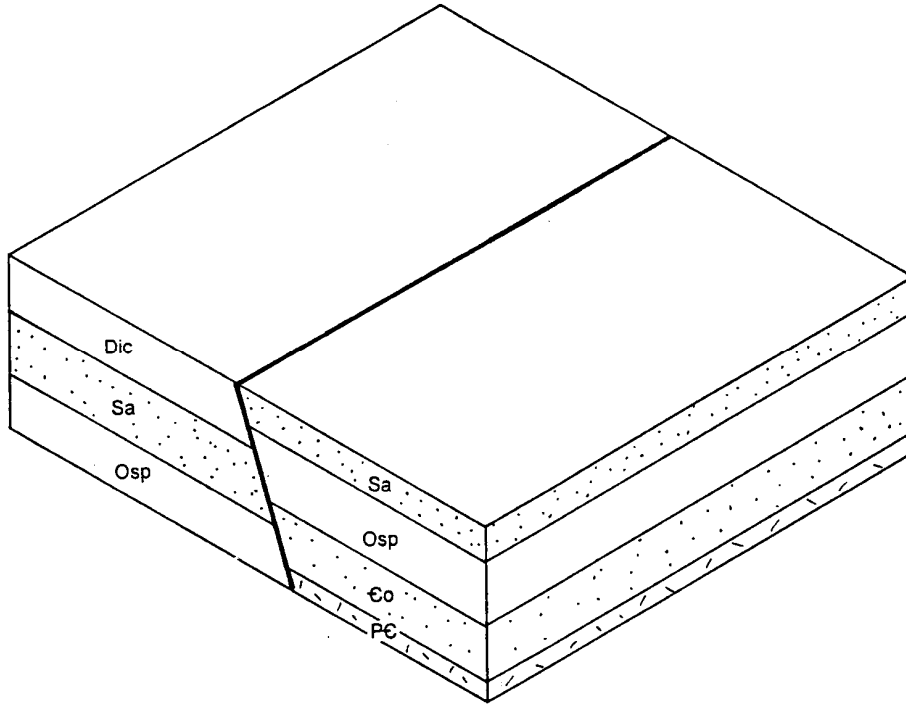
Calculation space

County map of the southeastern United States for use in solving Exercise 1.

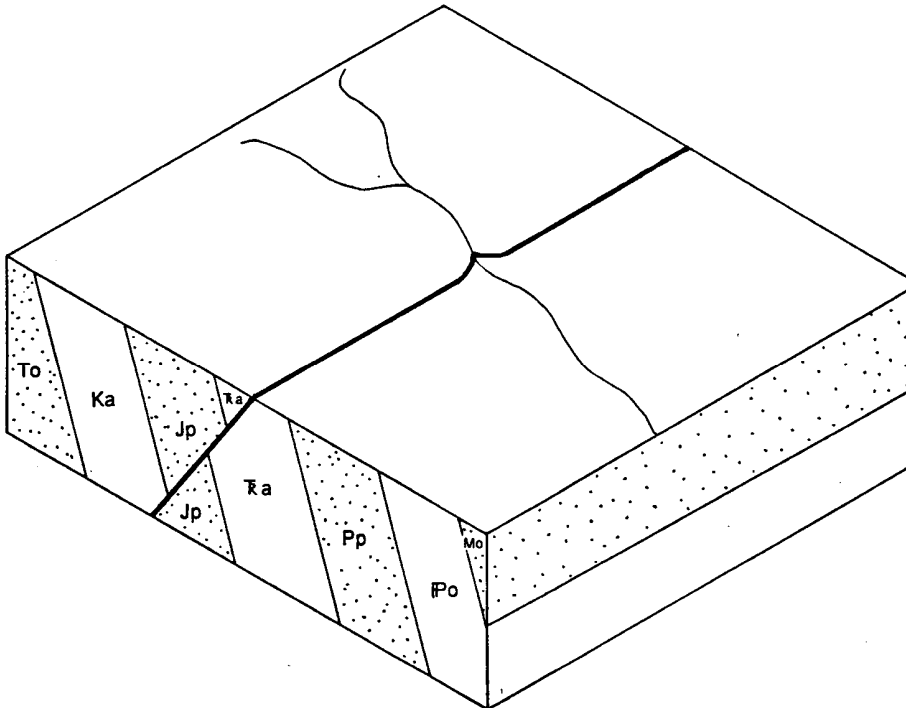


2) Complete the perspective diagrams of various fault structures and combinations of faults and folds that occur on the next several pages. For completeness, be sure to **add ALL relevant geological mapping symbols to the horizontal surface of each block diagram** (e.g., strike and dip symbols, slip movement, fold axes, plunge direction etc.). Remember to obey the Law of the "V"s. Also be sure to answer the additional question regarding the type of fault. Be specific! Calling it a dip slip fault or a strike slip fault is insufficient. Use normal, reverse, left lateral strike slip or right lateral strike slip. If you think a fault has both strike slip and dip slip motion, identify it as oblique slip. **(10 points each; total 60 points)**

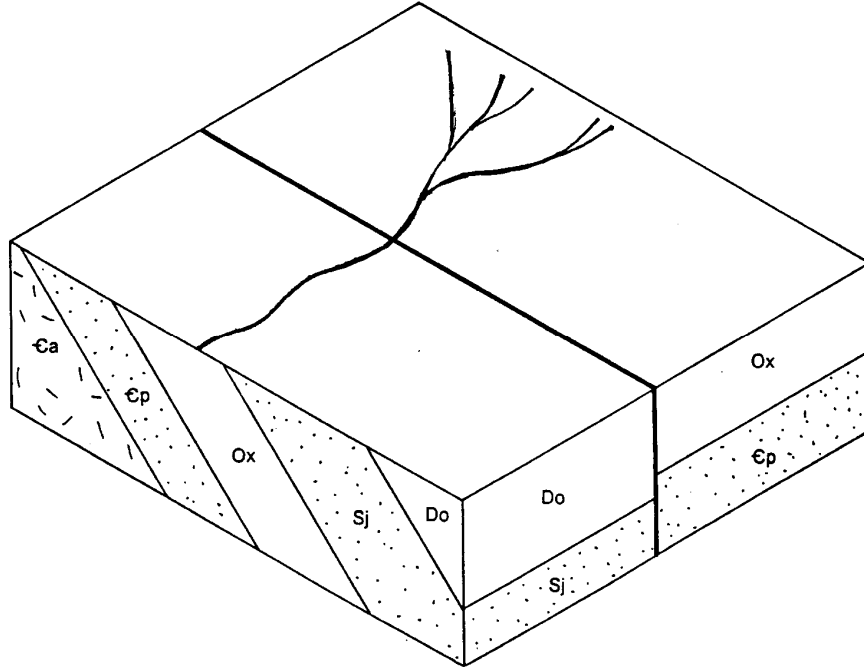
A) Kind of fault? _____



B) Kind of fault? _____

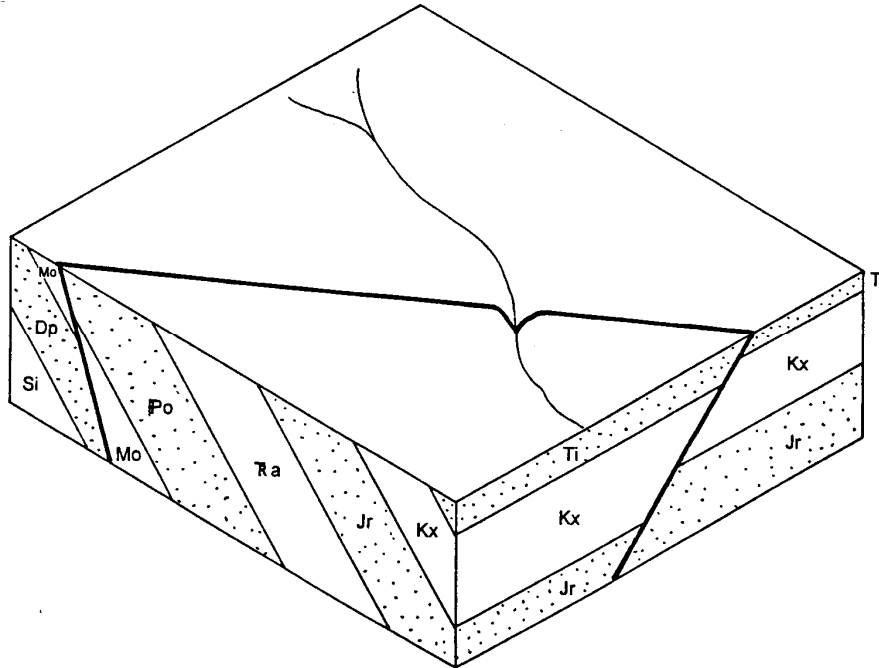


C) Kind of fault? _____

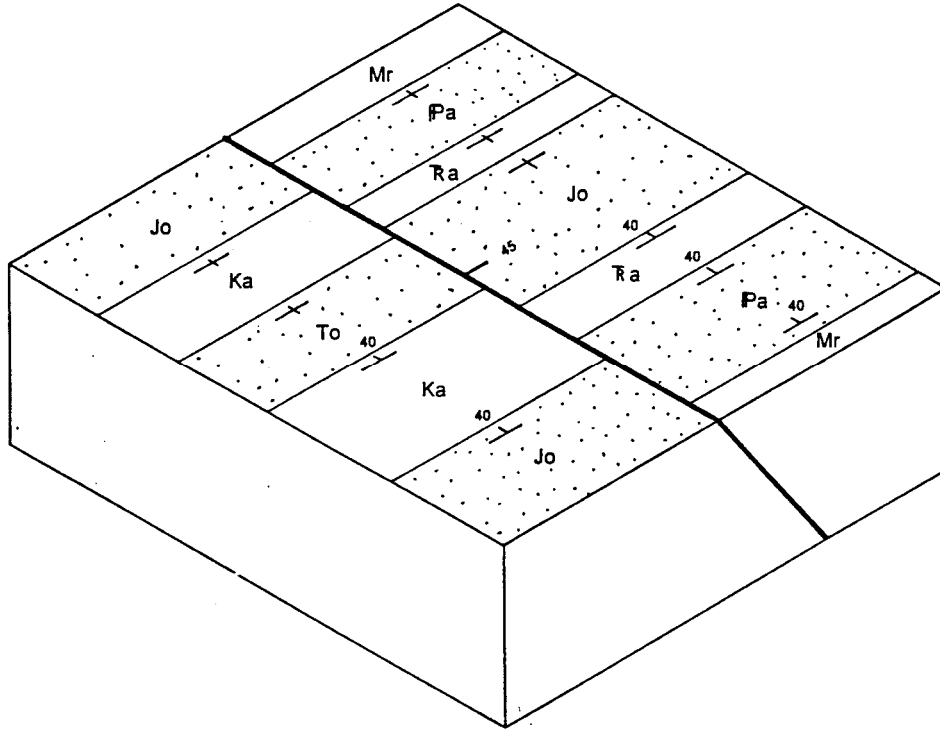


Note: The block diagram C is a bit tricky. There are two possible interpretations, but the river eliminates one of them. Why? _____

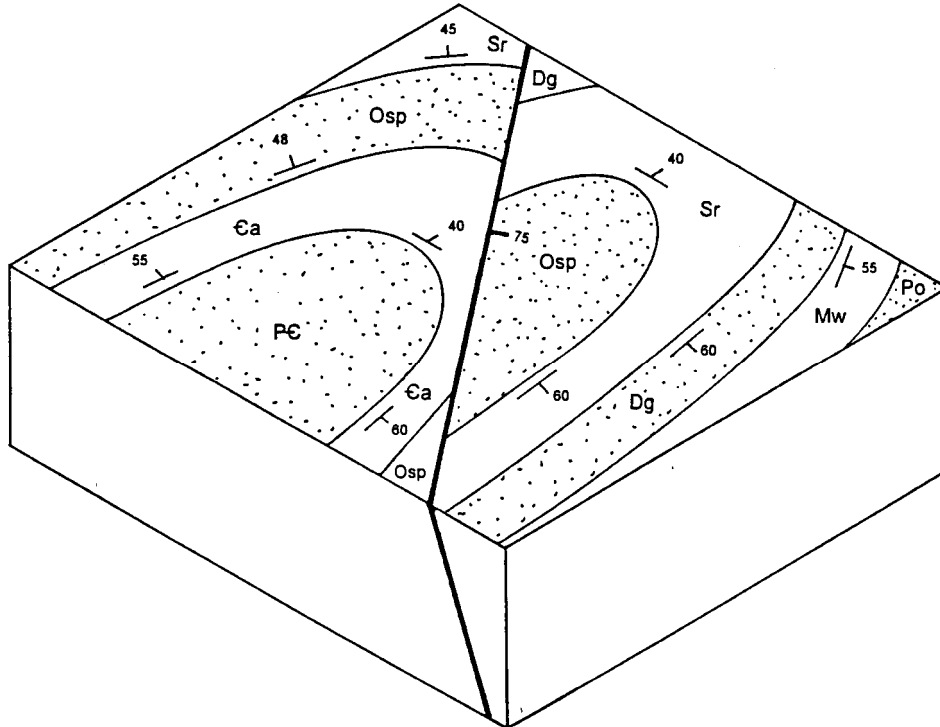
D) Kind of fault? _____



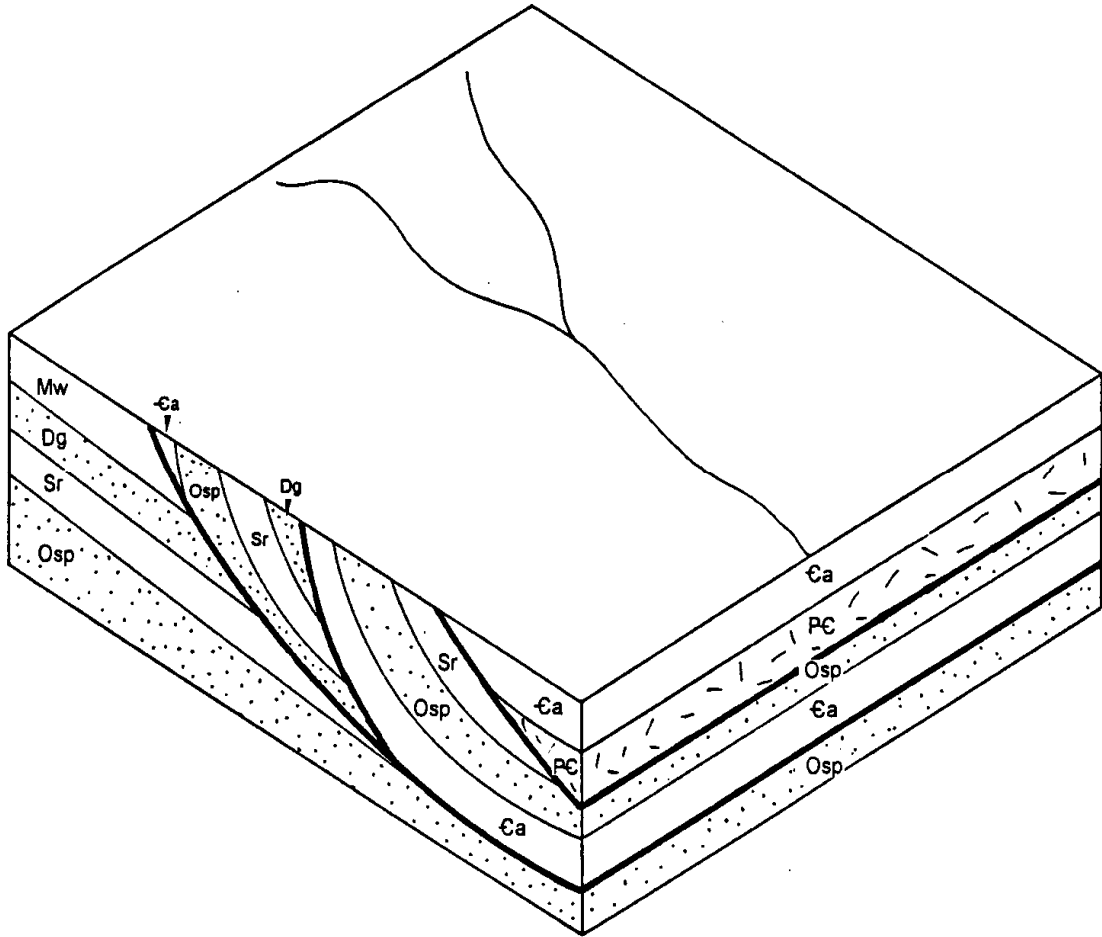
E) Kind of fault? _____



F) Kind of fault? _____



G) Kind of faults? _____



Optional Exercises

A) Past Lab Test: Here is another page from another one of Dr. Haywick's exams a few years ago. This time there are folds and faults on this map, but the complexity is still due entirely to folding [30 points]

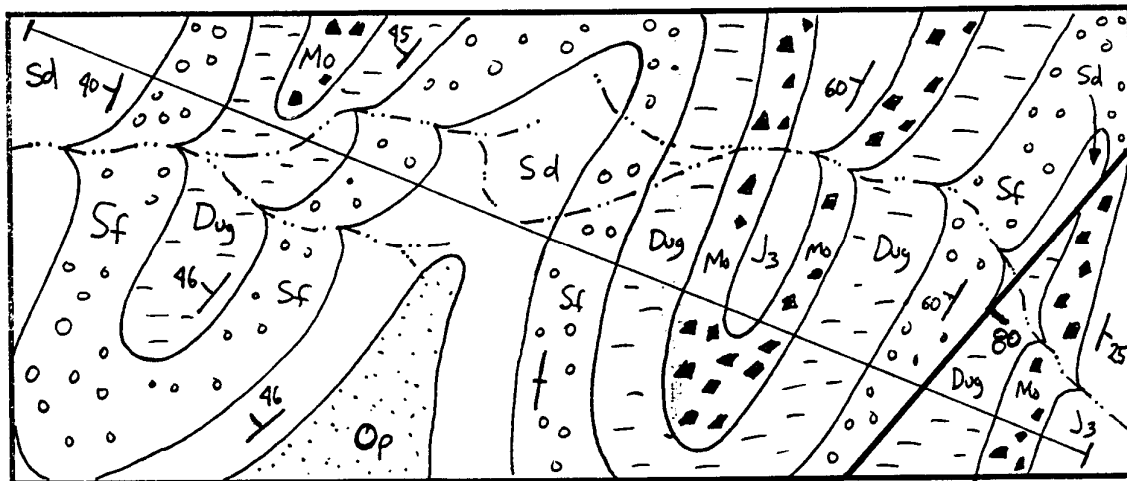
1) Draw all relevant fold, fault symbols, etc. (where necessary) on the map. [2 points]

2) Draw a geological cross-section along the line A-B [20 points]

3) What kind of fault occurs in the SE portion of the map sheet? _____ [3 points]

GEOLOGICAL MAP

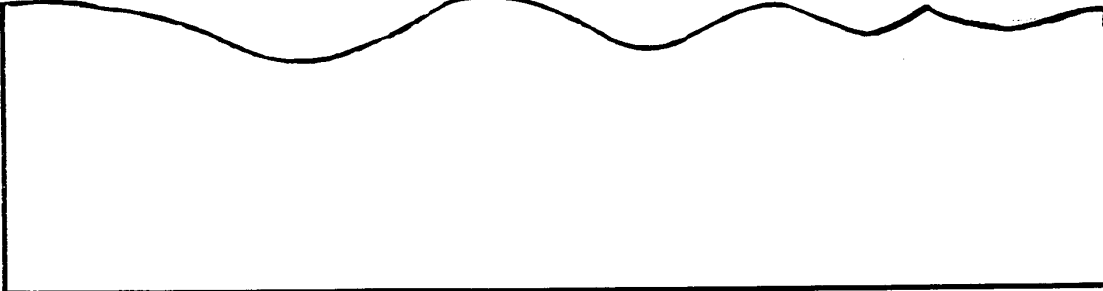
A



B

GEOLOGICAL CROSS-SECTION

A



B

<hr/> <p>Name</p>

Notes

