ภาควิชาธรณีวิทยา วิชา 2307551
คณะวิทยาศาสตร์ Geotectonics
จุฬาลงกรณ์มหาวิทยาลัย แบบฝึกหัดที่ 11 & 12
ชื่อนิสิต... รหัส....................................

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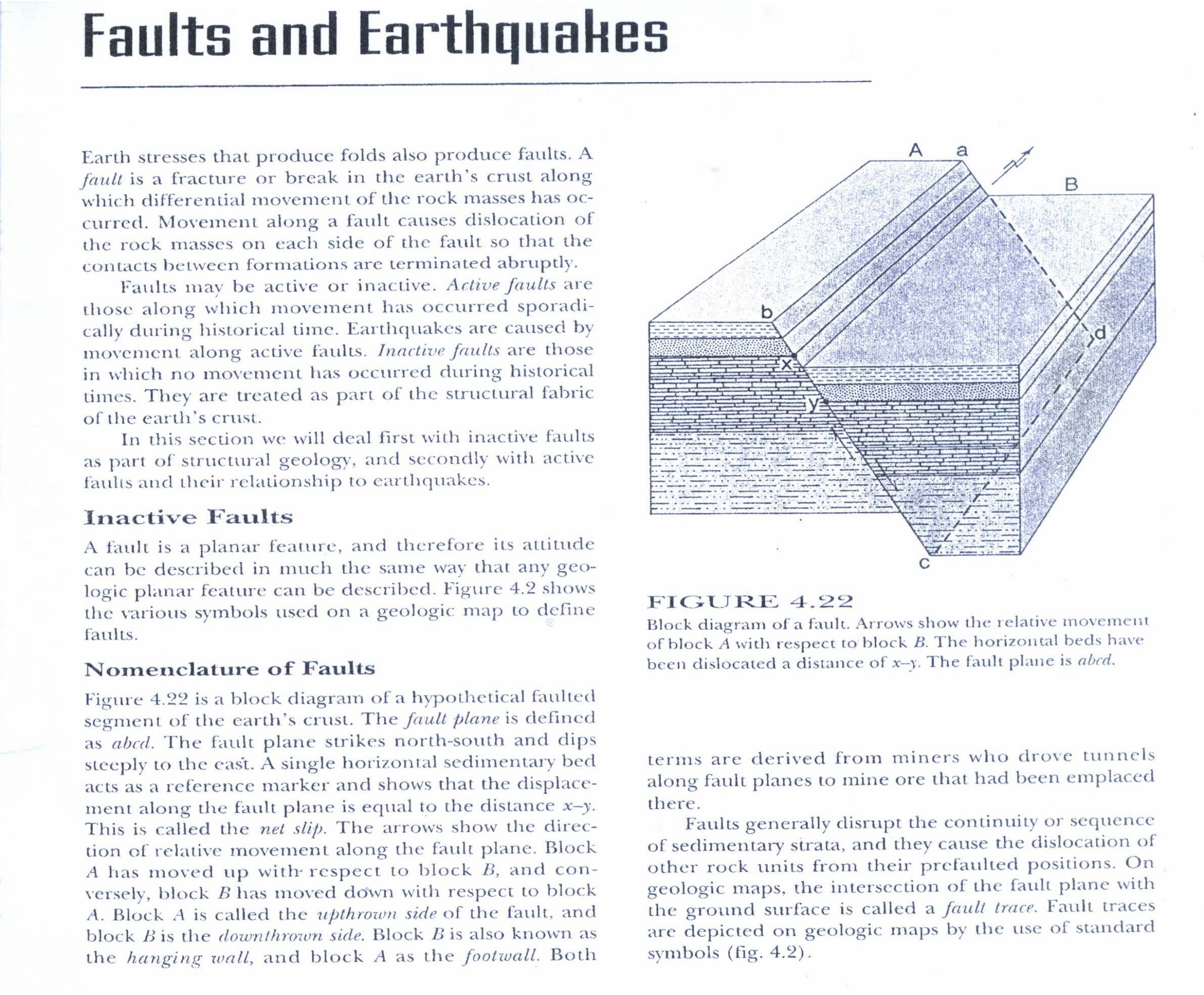
รอยเลื่อนและแผ่นดินไหว

วัตถุประสงค์ 1. เพื่อทราบลักษณะภูมิประเทศหลังเกิดรอยเลื่อน
2. เพื่อทราบตำแหน่งแผ่นดินไหวจากข้อมูลคลื่นสั่นสะเทือนจากสถานีวัด



Faults and Earthquakes

Earth stresses that produce folds also produce faults. A *fault* is a fracture or break in the earth's crust along which differential movement of the rock masses has occurred. Movement along a fault causes dislocation of the rock masses on each side of the fault so that the contacts between formations are terminated abruptly.

Faults may be active or inactive. *Active faults* are those along which movement has occurred sporadically during historical time. Earthquakes are caused by movement along active faults. *Inactive faults* are those in which no movement has occurred during historical times. They are treated as part of the structural fabric of the earth's crust.

In this section we will deal first with inactive faults as part of structural geology, and secondly with active faults and their relationship to earthquakes.

Inactive Faults

A fault is a planar feature, and therefore its attitude can be described in much the same way that any geologic planar feature can be described. Figure 4.2 shows the various symbols used on a geologic map to define faults.

Nomenclature of Faults

Figure 4.22 is a block diagram of a hypothetical faulted segment of the earth's crust. The *fault plane* is defined as *abcd*. The fault plane strikes north-south and dips steeply to the east. A single horizontal sedimentary bed acts as a reference marker and shows that the displacement along the fault plane is equal to the distance *x–y*. This is called the *net slip*. The arrows show the direction of relative movement along the fault plane. Block *A* has moved up with respect to block *B*, and conversely, block *B* has moved down with respect to block *A*. Block *A* is called the *upthrown side* of the fault, and block *B* is the *downthrown side*. Block *B* is also known as the *hanging wall*, and block *A* as the *footwall*. Both terms are derived from miners who drove tunnels along fault planes to mine ore that had been emplaced there.

FIGURE 4.22
Block diagram of a fault. Arrows show the relative movement of block *A* with respect to block *B*. The horizontal beds have been dislocated a distance of *x–y*. The fault plane is *abcd*.

Faults generally disrupt the continuity or sequence of sedimentary strata, and they cause the dislocation of other rock units from their prefaulted positions. On geologic maps, the intersection of the fault plane with the ground surface is called a *fault trace*. Fault traces are depicted on geologic maps by the use of standard symbols (fig. 4.2).

After faulting occurs, erosion usually destroys the surface evidence of the fault plane, so that with the passage of time the *fault scarp* (the exposed surface of the fault plane in figure 4.22) is destroyed. Only the fault trace remains.

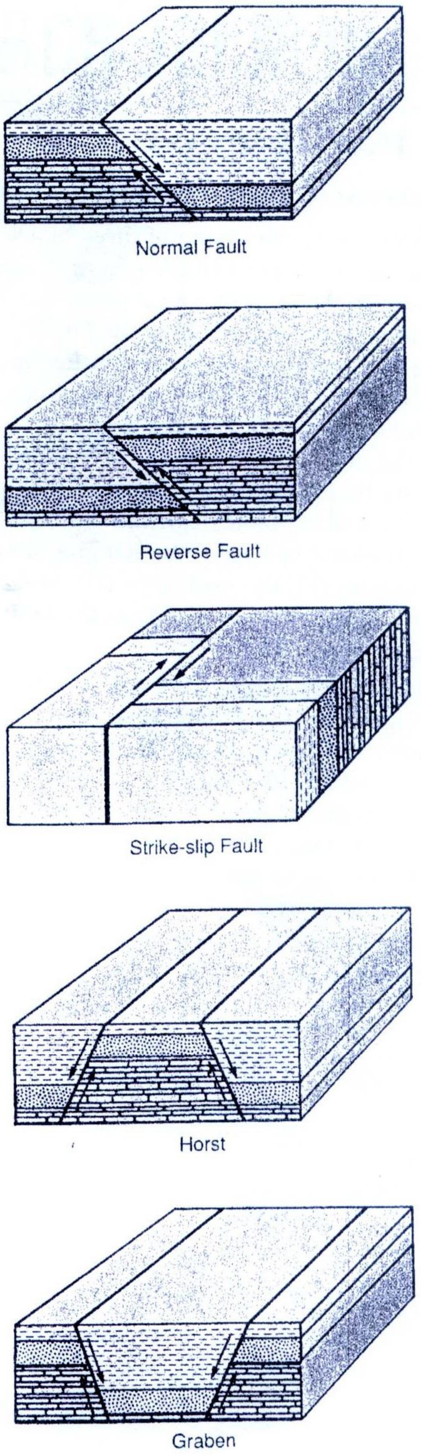
Types of Faults

Faults are divided into three major types, each of which is defined by the relative displacement along the fault plane. In the first two types, the main element of displacement has been vertical, more or less parallel to the dip of the fault plane. A *normal fault* is one in which the hanging wall has moved down relative to the footwall (fig. 4.23*A*). A *reverse fault* is one in which the hanging wall has moved up relative to the footwall (fig. 4.23*B*). A reverse fault in which the fault plane dips less than 45 degrees is called a *thrust fault.*

The third category of faults is characterized by relative displacement along the fault plane in a horizontal direction parallel to the strike of the fault plane. This type of fault is called a *strike-slip fault* (fig. 4.23*C*). Figure 4.23*D* shows a *horst,* an upthrown block bounded on its sides by normal faults. Figure 4.23*E* shows a *graben,* a downthrown block bounded on its sides by normal faults.

A fault shown on a geologic map can be analyzed to determine what kind of fault is involved. The analysis of normal and reverse faults will reveal the hanging and footwalls that lead to an understanding of the relative movement along the fault plane. In a strike-slip fault, off-setting of a marker bed as in figure 4.23*C* is the most direct evidence of the direction of movement. In some cases, the distinction between a strike-slip fault and a normal or reverse fault requires information not shown on the map.

A normal or reverse fault that cuts across the strike of inclined or folded sedimentary beds presents one of the most common situations for the analysis of movement along the fault plane. In such cases, there will be an apparent migration of the beds in the direction of dip of these beds on the upthrown side of the fault as erosion progresses. Stated another way, if an observer were to stand astride the fault trace, the observer's foot resting on the older rock would rest on the upthrown side. This is a simple mental test that can be applied to the analyses of faults presented in Exercise 23.


Normal Fault

Reverse Fault

Strike-slip Fault

Horst

Graben

FIGURE 4.23
Block diagrams illustrating major fault types. Arrows indicate relative movement along the fault plane.

EXERCISE 23A

Fault Problems

Fault Problems on Block Diagrams

1. In figure 4.24, the upper group of three block diagrams shows *A*, an unfaulted segment of the earth's crust with an incipient fault plane (dashed line); *B*, movement along the fault plane; and *C*, the appearance of the faulted area after erosion has reduced it to a relatively flat surface. The sequence *D, E,* and *F* is similar. Complete the outcrop patterns of the inclined formation on block diagrams *C* and *F* and label each as to the kind of fault ("normal" or "reverse"). Indicate by letters: the hanging wall (H), the footwall (F), the upthrown (U), and the downthrown side (D) on each side of the fault trace in diagrams *C* and *F*.
2. Figure 4.25 shows geologic maps *A* and *B*, and their corresponding block diagrams. The sedimentary formations are numbered according to their ages (stratum 1 is the oldest). Complete the block diagram below each map and indicate by letters on the map: the hanging wall (H), footwall (F), upthrown side (U), downthrown side (D), and show by arrows the relative movement along the fault plane. Label each fault as either "normal" or "reverse."
3. Figure 4.26 shows two separate sequences of three block diagrams: *A, B, C,* and *E, F, G.* Block diagrams *A* and *E* show conditions prior to faulting, *B* and *F* show conditions immediately after faulting, and *C* and *G* show the relationships on both sides of the fault traces after the fault scarp has been removed by erosion.
   - (*a*) Figure 4.26*D* is a geologic map of block diagram *C.* With a black pencil, draw the following symbols on the map: direction of dip of the fault plane; strike and dip symbols on the sedimentary beds on both sides of the fault trace; the upthrown (U) and downthrown (D) sides of the fault; and write either "normal" or "reverse" after the letter *D* at the lower margin of the map. (Refer to figure 4.2 to refresh your memory as to the various geologic map symbols.)
   - (*b*) In the blank space of figure 4.26*H,* draw a geologic map of block diagram *G,* draw the corresponding geologic map symbols as in 4.26*D,* and write either "normal" or "reverse" after the letter *H* on the lower margin of the map.

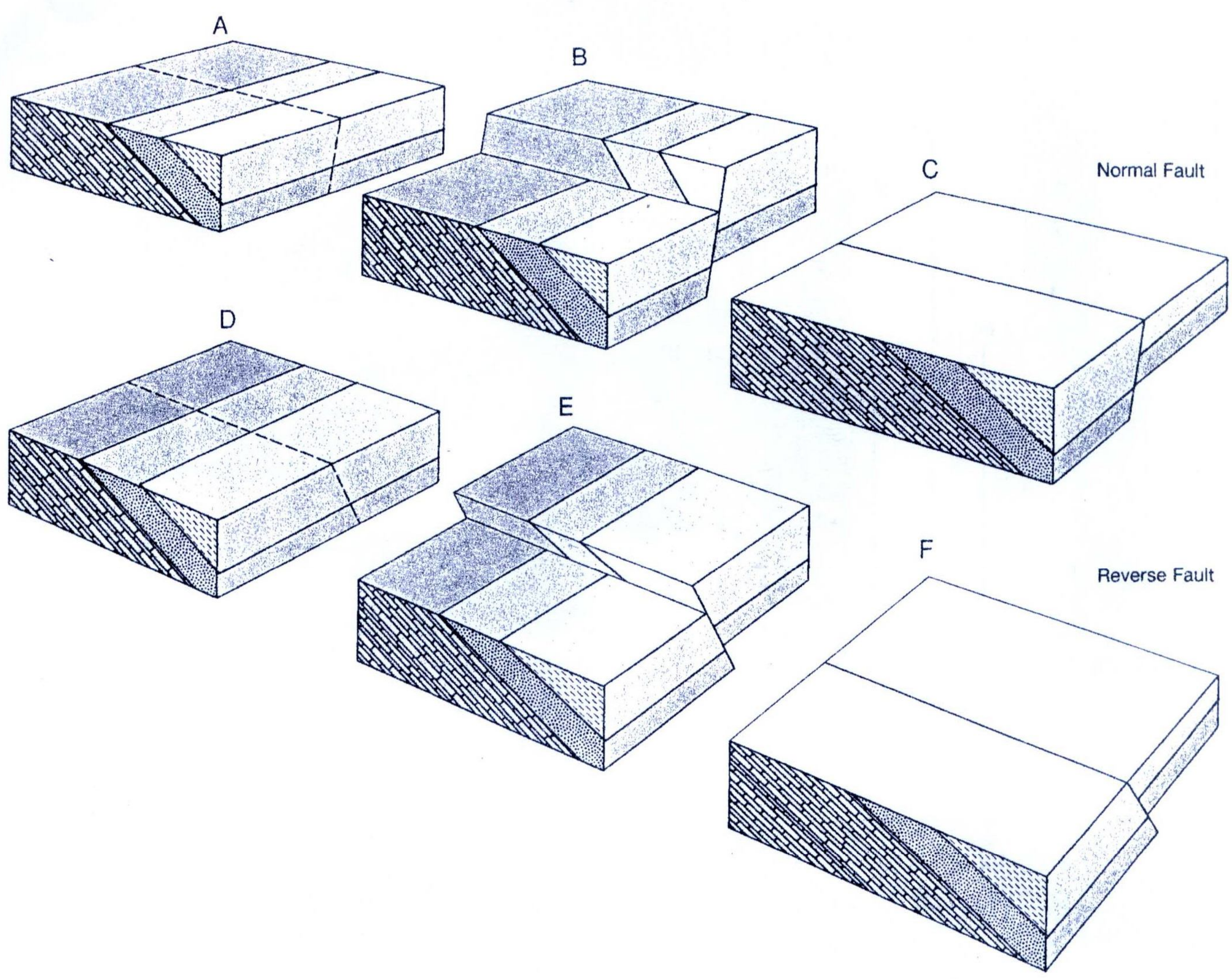
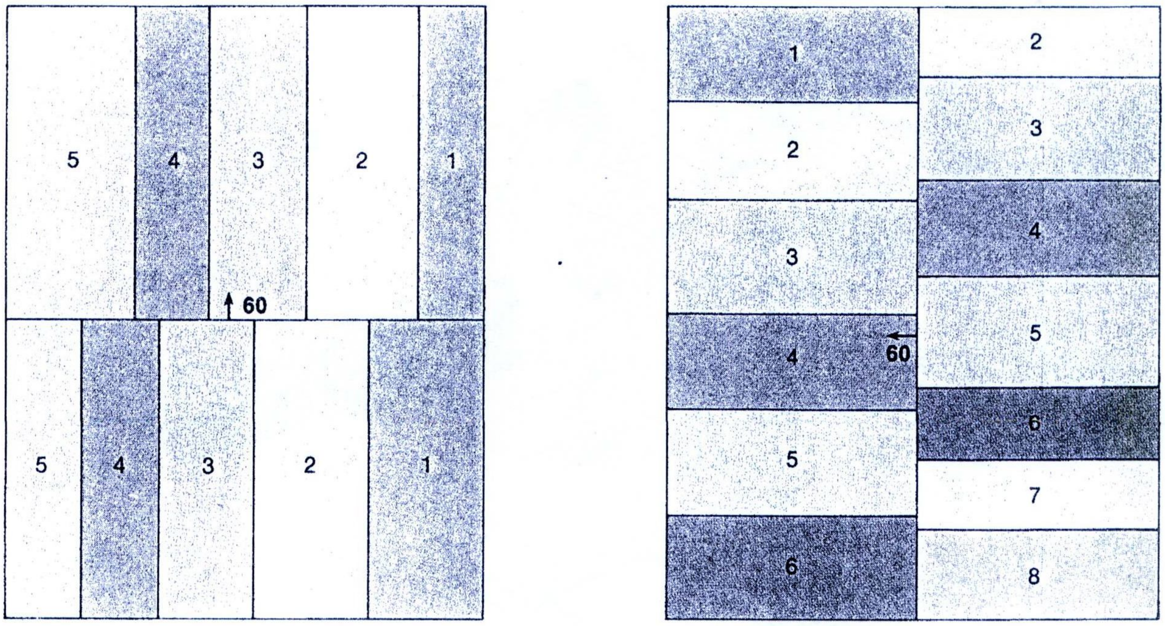


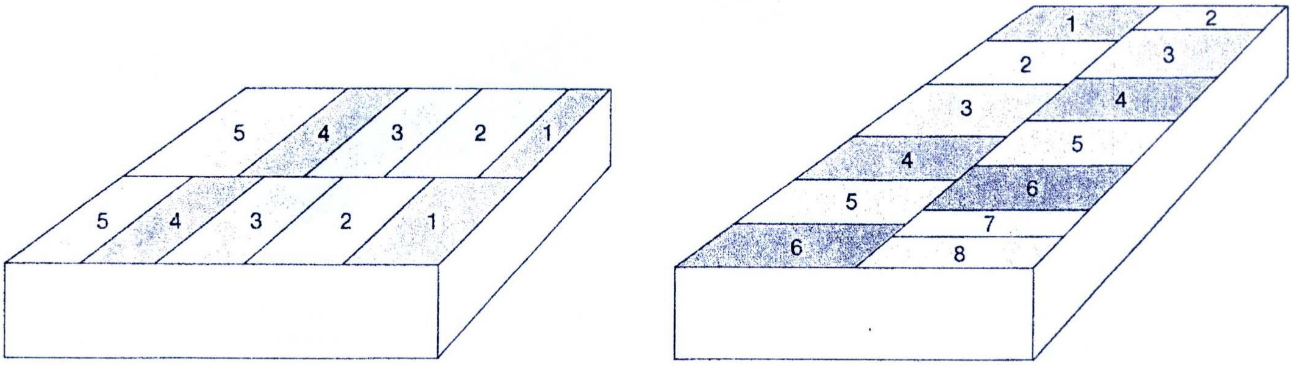
FIGURE 4.24

Series of block diagrams showing successive stages in the development of both a normal and a reverse fault—(*A*) and (*D*), before faulting with incipient fault plane marked by dashed line; (*B*) and (*E*), immediately after faulting; (*C*) and (*F*), after erosion of upthrown sides to a level common with the downthrown sides.



Geologic Map A

Geologic Map B



Block Diagram A

Block Diagram B

FIGURE 4.25
Block diagrams of faults and their corresponding geologic maps.

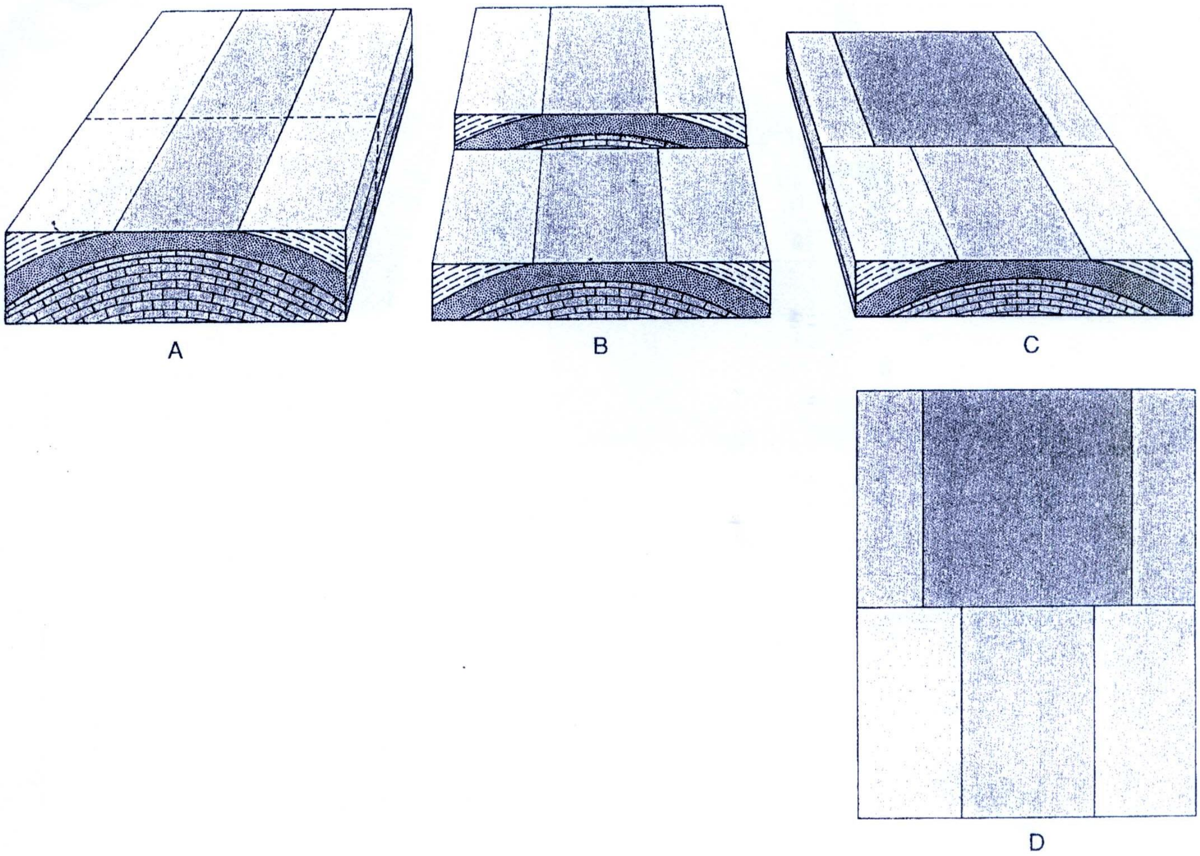


FIGURE 4.26
Block diagrams of a faulted anticline and faulted syncline.

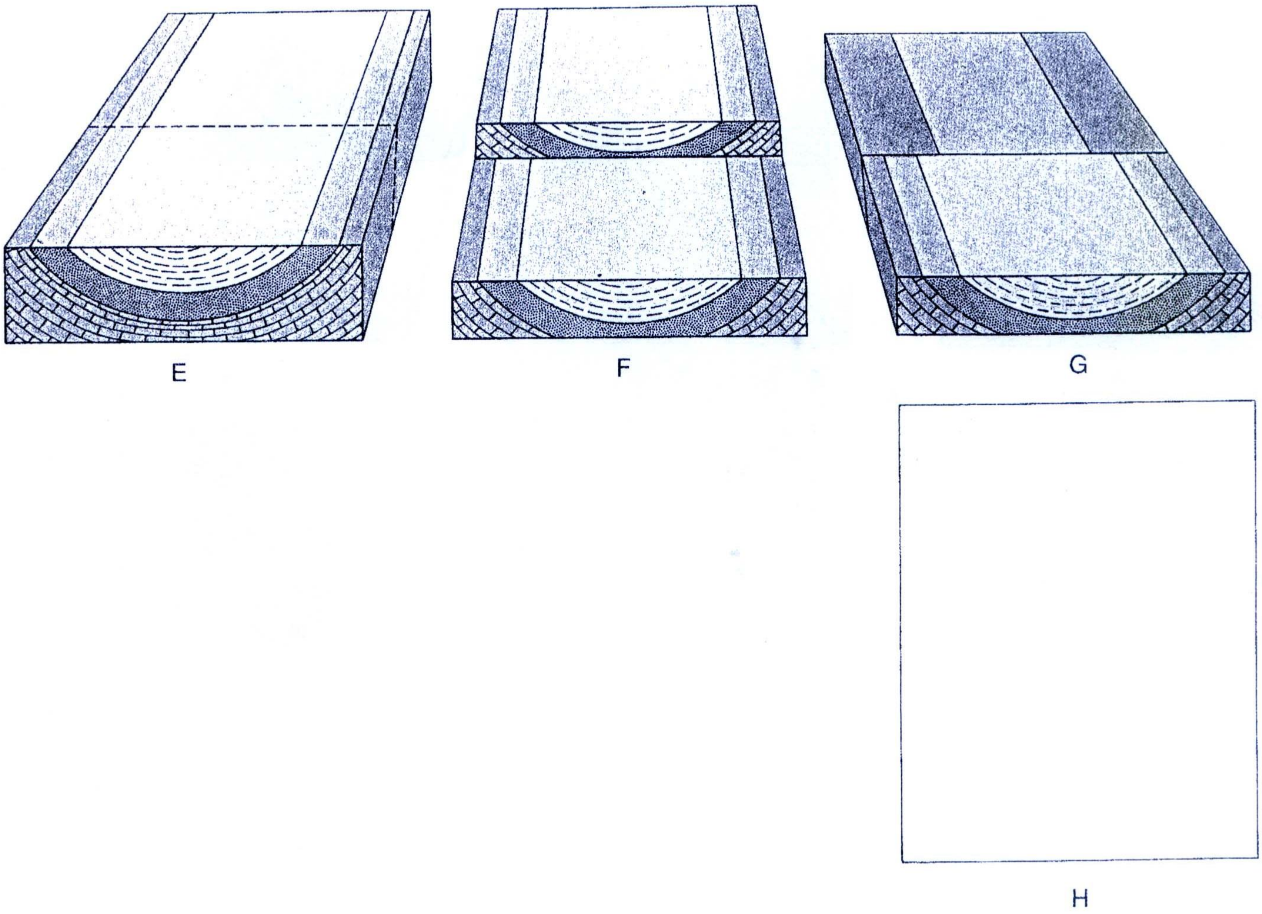


FIGURE 4.26—*Continued*

EXERCISE 23B

Fault Problems

Faulted Sedimentary Strata

1. On the Swan Island map (fig. 4.27), formation Ok is cut by a fault trending NW-SE. Label the upthrown and downthrown sides of the fault with the correct geologic symbols.
2. Refer to the fault described under question 1. What would be the direction of *dip* of the fault plane if this were a normal fault?
3. If the fault referred to in question 1 were a reverse fault, label the hanging-wall side with an "H."

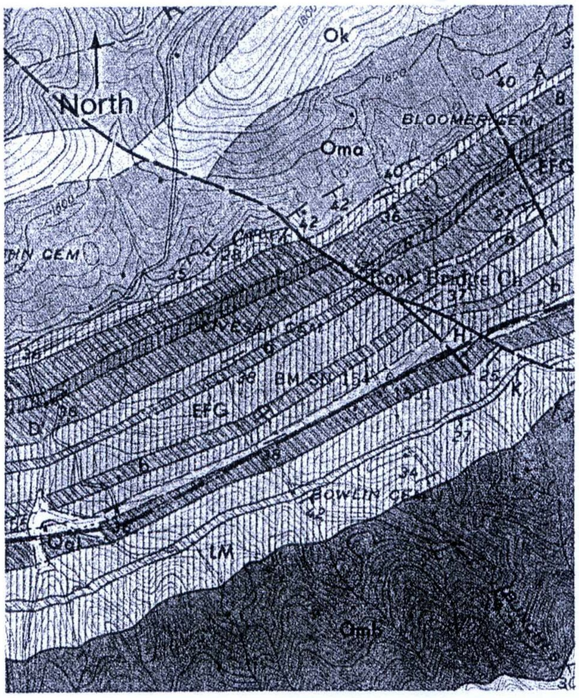


FIGURE 4.27

Part of the geologic map of Swan Island quadrangle, Tennessee, 1971. U.S. Geological Survey. Scale, 1:24,000; contour interval, 20 feet.

Active Faults

Fault Scarps and Fault Traces

The nomenclature of active faults is identical with the nomenclature of inactive faults. The attitude of an active fault plane may range from vertical to horizontal. Movement along the fault plane may produce a fault scarp at the earth's surface, but this scarp may be destroyed by erosion over time so that only a *trace* of the fault plane remains. Fault traces and fault scarps of both active and inactive faults can be identified on aerial photographs or images from earth-orbiting satellites by abrupt changes in topography or color patterns.

Earthquake Epicenters and Foci

The place where movement begins on the fault plane marks the *focus* of the resulting earthquake, and the point on the earth's surface vertically above the focus is the *epicenter* of the earthquake (fig. 4.28). The focus and epicenter of an earthquake that is generated on a vertical fault plane define the fault plane as a line on a cross section. If the earthquake is generated by movement along an inclined fault plane, the fault plane is defined in cross section by a line passing through the focus and the fault scarp or fault trace at the earth's surface. When movement occurs along a fault plane, energy is released and an earthquake is produced.

Reference

Greensfelder, Roger. 1971. Seismologic and crustal movement investigations of the San Fernando earthquake. *California Geology*, April-May 1971: 62–68. California Division of Mines and Geology, Sacramento, California 95814.

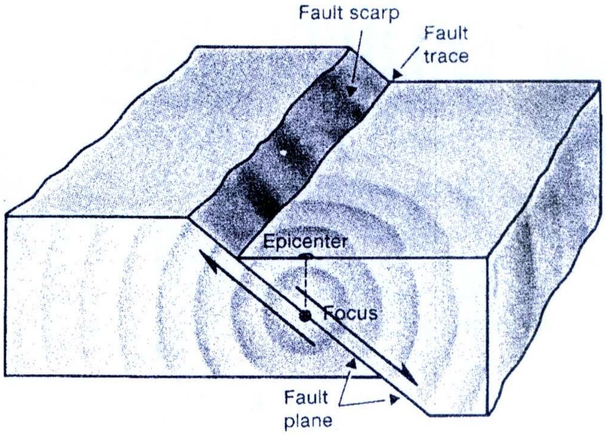
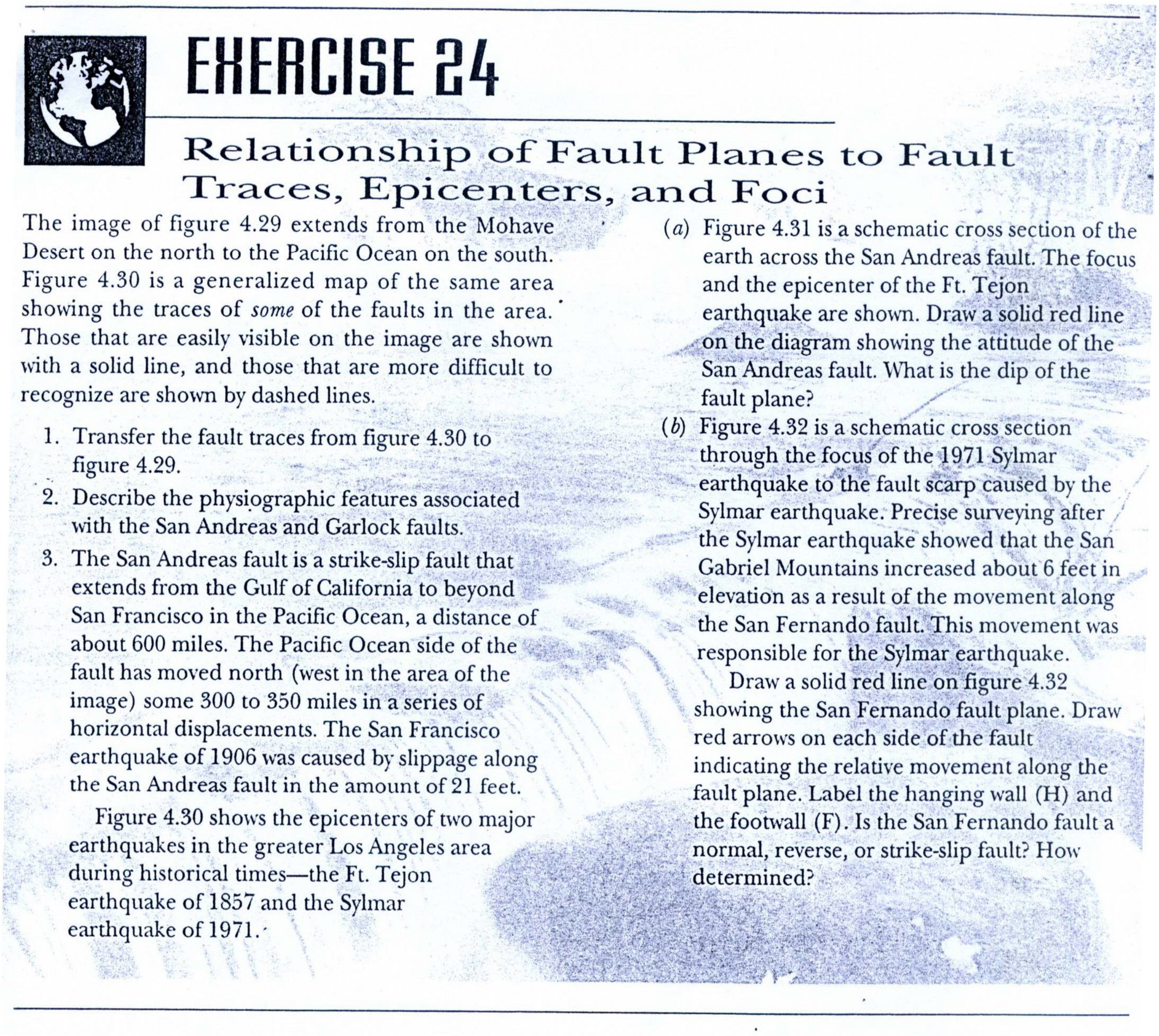


FIGURE 4.28
Block diagram showing a fault plane and the focus and epicenter of an earthquake generated by movement along the fault. Arrows show direction of relative movement along the fault and concentric shaded circles show the propagation of seismic waves. (From Carla W. Montgomery, *Physical Geology*, 3d ed. Copyright © 1993 Wm. C. Brown Communications, Inc., Dubuque, Iowa. All Rights Reserved. Reprinted by permission.)



EXERCISE 24

Relationship of Fault Planes to Fault Traces, Epicenters, and Foci

The image of figure 4.29 extends from the Mohave Desert on the north to the Pacific Ocean on the south. Figure 4.30 is a generalized map of the same area showing the traces of *some* of the faults in the area. Those that are easily visible on the image are shown with a solid line, and those that are more difficult to recognize are shown by dashed lines.

1. Transfer the fault traces from figure 4.30 to figure 4.29.
2. Describe the physiographic features associated with the San Andreas and Garlock faults.
3. The San Andreas fault is a strike-slip fault that extends from the Gulf of California to beyond San Francisco in the Pacific Ocean, a distance of about 600 miles. The Pacific Ocean side of the fault has moved north (west in the area of the image) some 300 to 350 miles in a series of horizontal displacements. The San Francisco earthquake of 1906 was caused by slippage along the San Andreas fault in the amount of 21 feet.

   Figure 4.30 shows the epicenters of two major earthquakes in the greater Los Angeles area during historical times—the Ft. Tejon earthquake of 1857 and the Sylmar earthquake of 1971.

   (*a*) Figure 4.31 is a schematic cross section of the earth across the San Andreas fault. The focus and the epicenter of the Ft. Tejon earthquake are shown. Draw a solid red line on the diagram showing the attitude of the San Andreas fault. What is the dip of the fault plane?

   (*b*) Figure 4.32 is a schematic cross section through the focus of the 1971 Sylmar earthquake to the fault scarp caused by the Sylmar earthquake. Precise surveying after the Sylmar earthquake showed that the San Gabriel Mountains increased about 6 feet in elevation as a result of the movement along the San Fernando fault. This movement was responsible for the Sylmar earthquake.

   Draw a solid red line on figure 4.32 showing the San Fernando fault plane. Draw red arrows on each side of the fault indicating the relative movement along the fault plane. Label the hanging wall (H) and the footwall (F). Is the San Fernando fault a normal, reverse, or strike-slip fault? How determined?

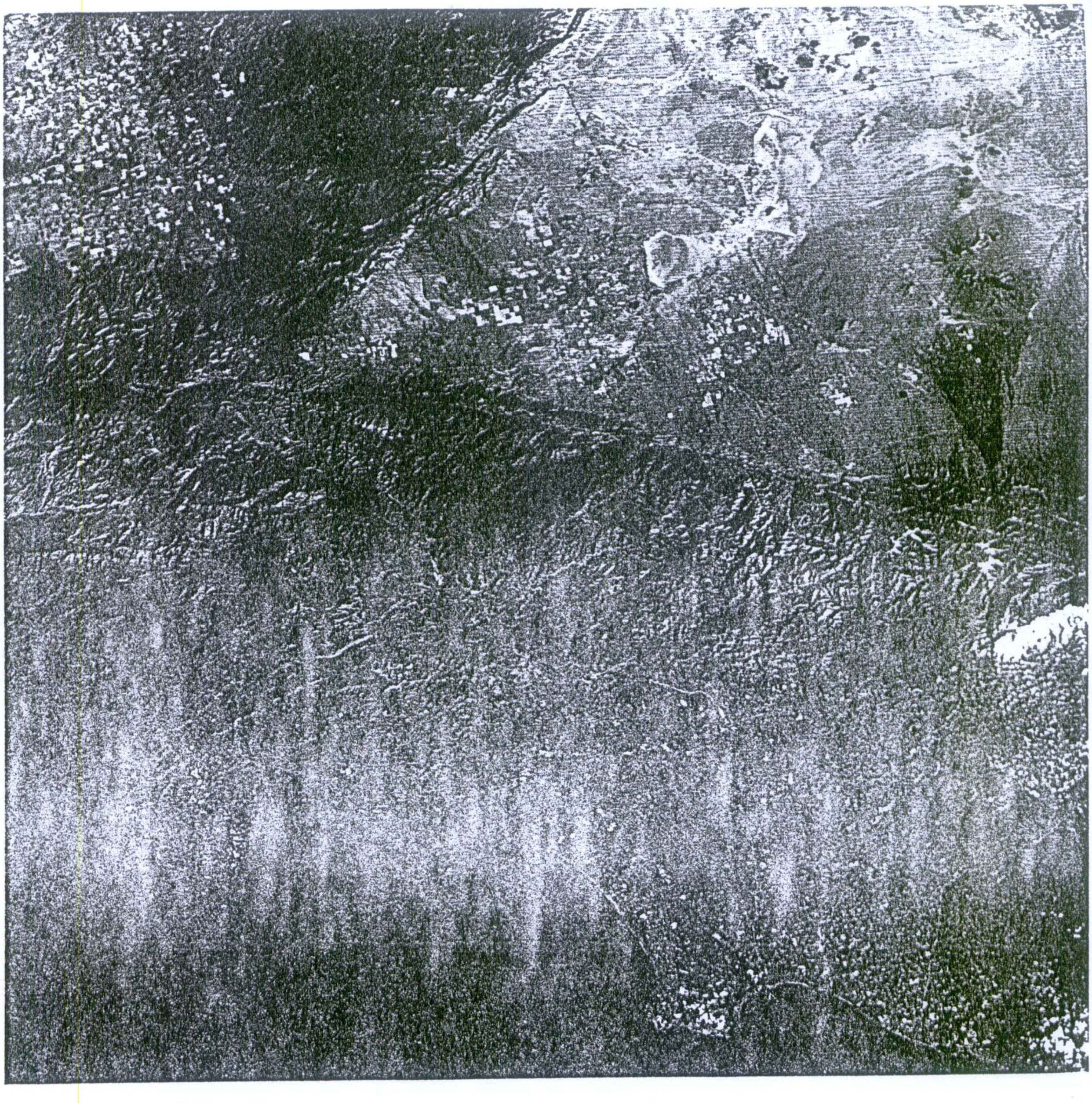


FIGURE 4.29

False color image of the greater Los Angeles area of southern California, made from Landsat 1, October 21, 1972. (NASA ERTS image E–1090–180 12.)

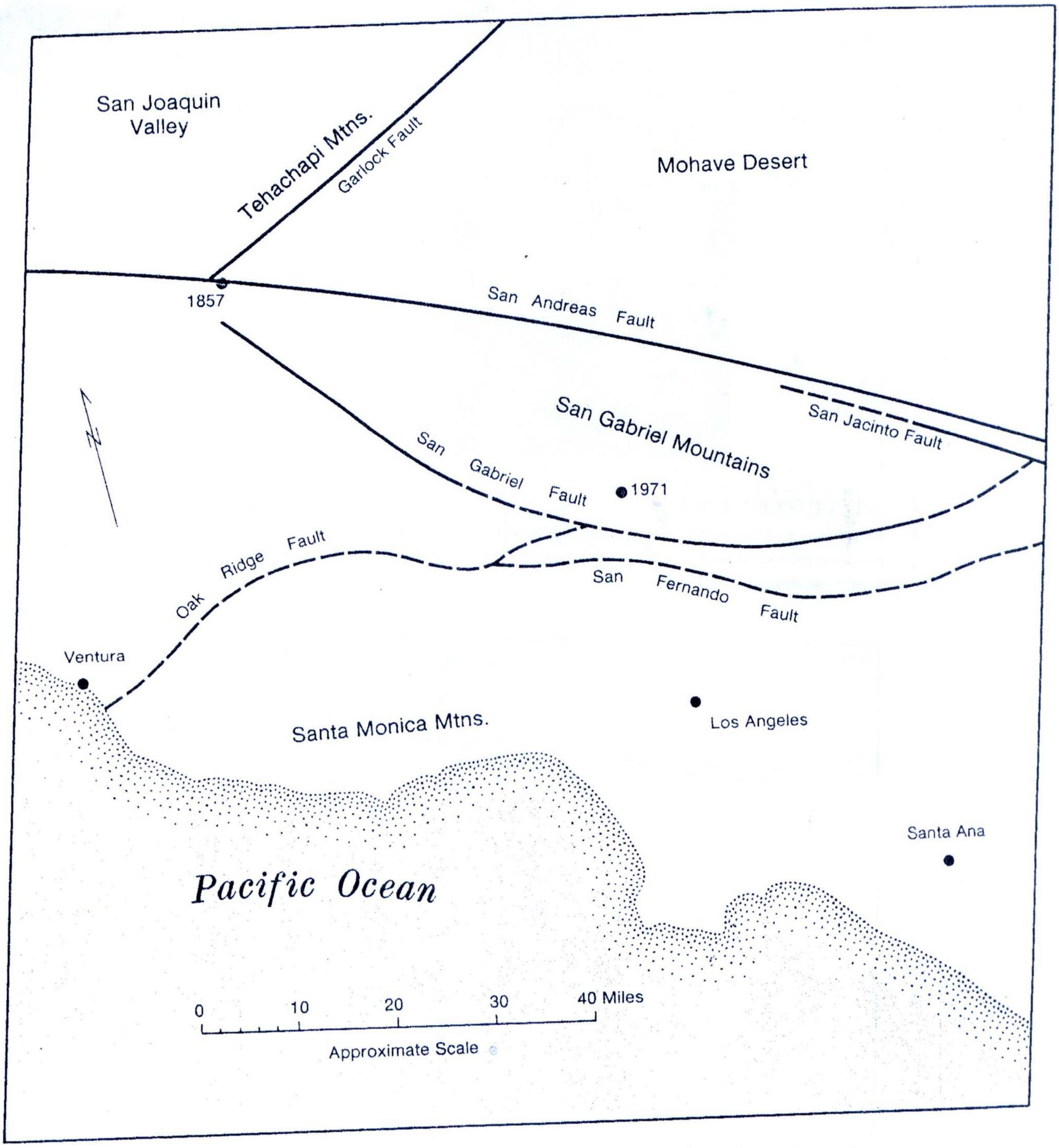


FIGURE 4.30
Generalized map of the greater Los Angeles area showing traces of some of the faults occurring there, also the epicenters of the Ft. Tejon earthquake of 1857 and the Sylmar earthquake of 1971. (Source: R. H. Campbell, 1976. "Active faults in the Los Angeles-Ventura area of Southern California." *ERTS–1: A New Window on Our Planet,* U.S. Geological Survey Professional Paper 929, pp. 113–16.)

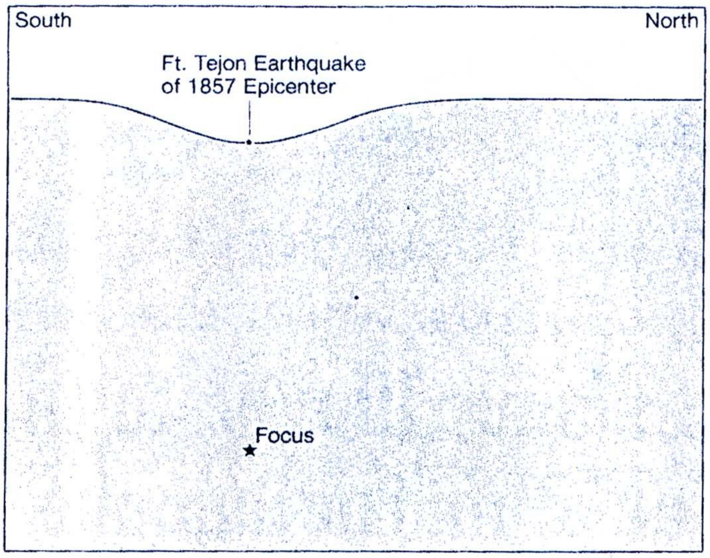


FIGURE 4.31

Schematic north-south cross section across the trace of the San Andreas fault showing the epicenter and focus of the Ft. Tejon earthquake of 1857.

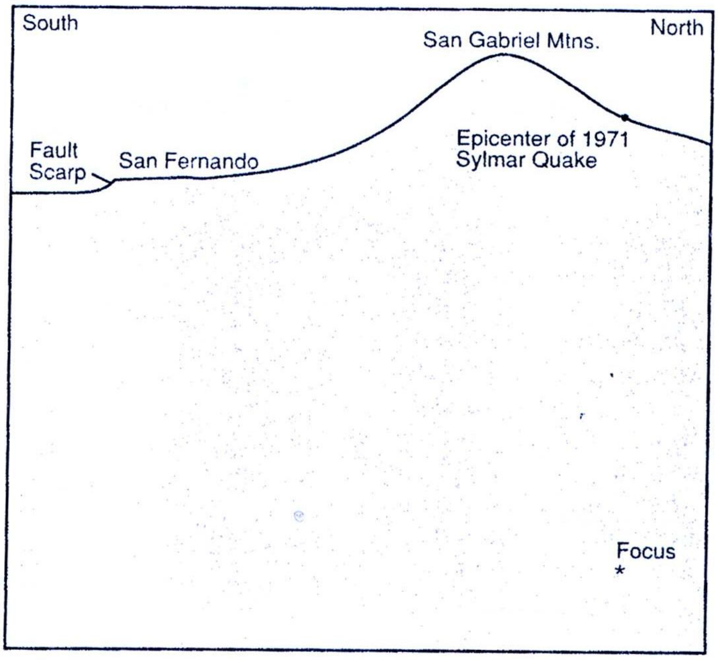
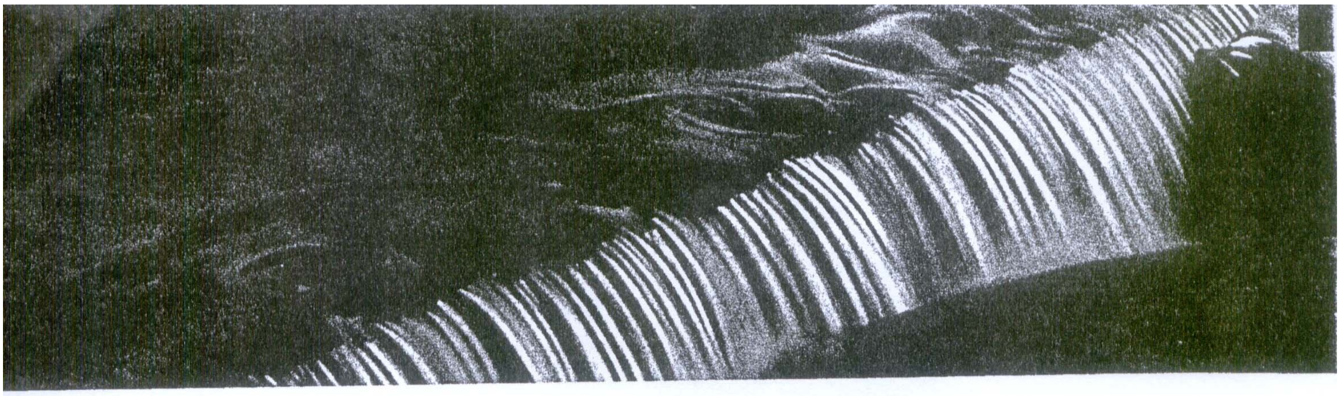


FIGURE 4.32

Schematic north-south cross section from San Fernando across the San Gabriel Mountains through the epicenter of the Sylmar earthquake of 1971. Vertical scale exaggerated. (Cross section adapted from Greensfelder, R., 1971, "Seismological and crustal movement investigations of the San Fernando earthquake" in *California Geology,* April–May.)



The Use of Seismic Waves to Locate the Epicenter of an Earthquake

Seismographs, Seismograms, and Seismic Observatories

The energy released by an earthquake produces vibrations in the form of *seismic waves* that are propagated in all directions from the focus. Seismic waves can be detected by an instrument called a *seismograph,* and the record produced by a seismograph is called a *seismogram.* The geographical location of a seismograph is called a *seismic station* or *seismic observatory,* and it is given a name in the form of a code consisting of three or four capital letters that are an abbreviation of the full name of the station. For example, a seismic observatory on Mt. Palomar, in southern California, has the code designation of PLM. A worldwide network of seismic observatories provides records of the times of arrival of the various kinds of seismic waves. Seismograms from at least three different stations located around the focus of a given earthquake but at some distance from it provide the data needed to locate the epicenter.

Seismic Waves

Two general types of seismic waves are generated by an earthquake: *body waves* and *surface waves.* Body waves travel from the focus in all directions through the earth; they penetrate the "body" of the earth. Surface waves travel along the surface of the earth and do not figure in the location of an epicenter.

Body waves consist of *primary waves* and *secondary waves.* The primary wave is referred to as the *P wave,* and the secondary wave is the *S wave.* The P wave is like a sound wave in that it vibrates in a direction parallel to its direction of propagation. An S wave, on the other hand, vibrates at right angles to the direction of wave propagation (fig. 4.33).

P and S waves are generated at the same time at the focus, but they travel at different speeds. The P wave travels almost twice as fast as the S wave and is always the first wave to arrive at the seismic station. The S wave follows some seconds or minutes after the first arrival of the P wave. *The difference in arrival times of the P and S waves is a function of the distance from the seismic station to the epicenter.* The distance from the seismic station to the epicenter is called the *epicentral distance.*

Reading a Seismogram

A seismograph records the incoming seismic waves as wiggly lines on a piece of paper wrapped around a drum rotating at a fixed rate of speed. The resulting seismogram contains not only the record of the incoming seismic waves but also marks that indicate each minute of time. Clocks at all seismic stations around the world are set at Greenwich Mean Time (GMT), so no matter what time zones observatories are located in, the seismograms produced at them are all based on a standardized clock.

When no seismic waves are arriving at an observatory, the seismograph draws a more or less straight line (fig. 4.34). Some small irregular wiggles on the seismogram may be *background noise* from vibrations produced by trucks, trains, heavy surf, construction equipment, and the like. Most modern seismographs contain a damping mechanism that reduces background noise to a minimum. In addition, background noise is kept to a minimum if the observatory is located in a remote area where human activities are uncommon.

The time of arrival of the first P wave is noted as T_P. The P wave continues to arrive until the first S wave appears, which is noted as T_S. The S wave has a much larger amplitude than the P wave. (The amplitude is

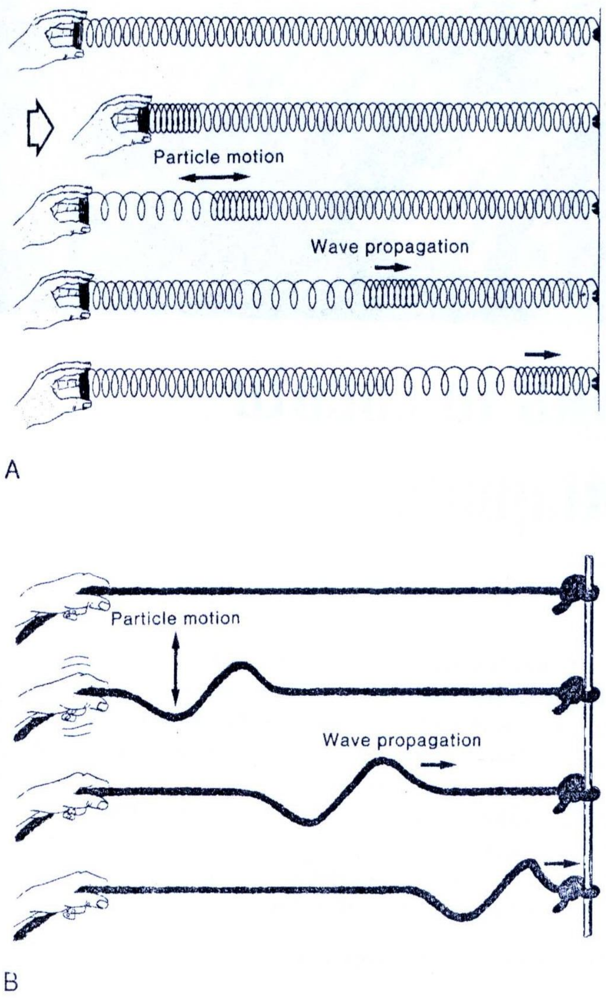


FIGURE 4.33

Particle motion in seismic waves. (*A*) P wave is illustrated by a sudden push on the end of a stretched spring. The particles vibrate *parallel* to the direction of wave propagation. (*B*) S wave is illustrated by shaking a loop along a stretched rope. The particles vibrate *perpendicular* to the direct wave propagation. (From Charles C. Plummer and David McGeary, *Physical Geology,* 6th ed. Copyright © 1993 Wm. C. Brown Communications, Inc., Dubuque, Iowa. All rights reserved. Reprinted by permission.)

the vertical distance between the peak of the recorded wave and the line on the seismogram recorded when no seismic waves are arriving.)

Figure 4.34 shows a seismogram from the Santa Ynez Peak Observatory on which the arrival times of the P and S waves are shown as T_p and T_s. These were determined by using the time scale on the seismogram to measure the time from the mark labeled 12:40:00 (12 hrs: 40 min: 00 sec) to the times of arrival of the first P and S waves. On the SYP seismogram of figure 4.34, T_p is 19 seconds after the time mark, or 12:40:19 GMT, and T_s is 44 seconds after the time mark, or 12:40:44 GMT. The difference between the time of arrivals, $T_s - T_p$, is therefore 25 seconds.

Locating an Epicenter on a Map Using Travel-Time Curves

$T_s - T_p$ is measured in units of time, and this time, when converted to a distance, indicates the epicentral distance. Converting this time to distance requires the use of *travel-time curves* for both the P and S waves as shown in figure 4.35. A point on either one of the curves indicates the time required for a P or S wave to travel a certain distance from the epicenter. Time in seconds is shown on the vertical scale, and the corresponding distance in kilometers is shown on the horizontal scale. Following is the procedure for converting $T_s - T_p$ in seconds to an epicentral distance in kilometers:

1. Determine T_p and T_s from a seismogram to the nearest second. Record these values for use in the next step.
2. Subtract T_p from T_s and record as a time in seconds for use in the next step.
3. On the vertical axis of the travel-time graph of figure 4.35, set one point of a divider or compass on zero, and the other point on the value of $T_s - T_p$.
4. Move the compass upward and to the right until the point formerly on zero lies on the P curve and the other point lies on the S curve immediately above. It is important that the two points of the compass be on a vertical line in order to obtain the correct reading. Holding the compass in place, follow the vertical line on which the two points rest down to the horizontal scale, and read and record the epicentral distance.

   As an example of this procedure, let us use the data from the SYP seismogram of figure 4.34. The value for $T_s - T_p$ on this seismogram is 25 seconds. With one point of the divider set on zero of the vertical axis of figure 4.35, we set the other point on 25. Then, with the compass at this setting, we move it between the P and S wave curves until one point of the compass is on the P wave curve and the other point is directly above it on the S wave curve. We follow the vertical line on which the two points rest down to the bottom scale and read 192 kilometers, the epicentral distance at station SYP.
5. On a suitable base map, use the bar scale on the map to *reset* your compass to the epicentral distance determined in step 4. Use this compass setting to draw a circle on the map whose center is at the geographic coordinates of the appropriate seismic station.
6. By following steps 1 through 5 for three different seismograms at appropriate directions and distances from the epicenter, you will draw three circles that intersect or nearly intersect at the epicenter.

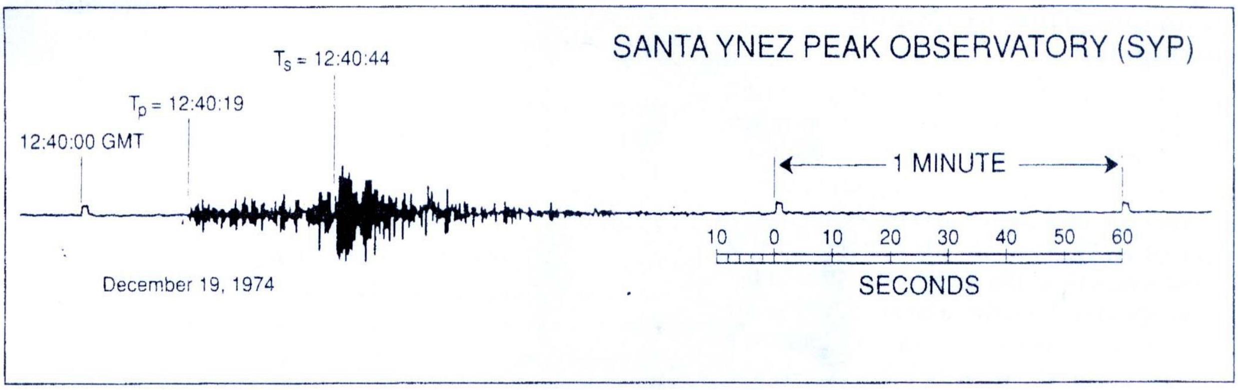


FIGURE 4.34
A seismogram recorded at the Santa Ynez Peak Observatory (SYP) in California showing an earthquake on December 19, 1974. The time mark automatically recorded on the seismogram is 12:40:00, which is 12:40 P.M. Greenwich Mean Time (GMT). The time of arrival of the first P wave, T_p, is 12:40:19, and the time of arrival of the first S wave, T_s, is 12:40:44. (Source: Based on data from Charles G. Sammis, University of Southern California.)

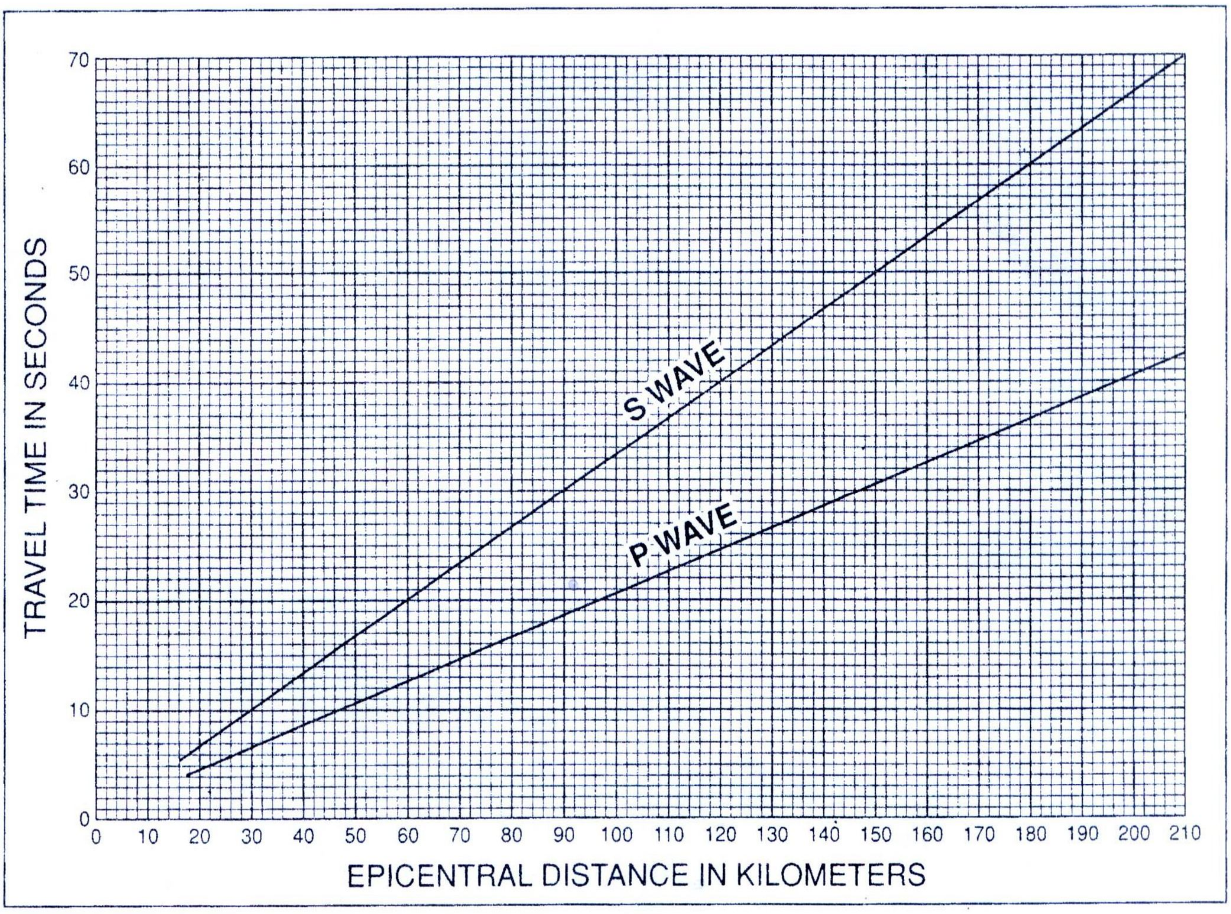


FIGURE 4.35
Travel-time curves for P and S waves in southern California. (Source: Based on data from Charles G. Sammis, University of Southern California.)

Determining the Time of Origin of an Earthquake

The epicentral distances determined from $T_s - T_p$ are used to find the time of origin of the earthquake, designated by the symbol T_o. The procedure to do this is best explained by an example. Let us return to the information from the seismogram, recorded at station SYP, of figure 4.34. We have already determined that the epicentral distance is 192 kilometers. Remember that this is the distance from the seismic station to the epicenter of the earthquake. We want to know the time when this earthquake occurred, T_o. That is also the time when the seismic waves started their journey of 192 kilometers to SYP. Looking at figure 4.35, we see that the point where the P wave curve intersects the 192-kilometer line is 39 seconds. This tells us that it took the P wave 39 seconds to travel from the earthquake epicenter to station SYP. T_o is determined by subtracting the travel time of the P wave, 39 seconds, from T_p which is 12:40:19 GMT. Subtracting 39 seconds from 12 hrs, 40 minutes, 19 seconds gives us 12:39:40 GMT, the time of origin of the earthquake, or T_o.

References

Bolt, Bruce. 1978. *Earthquakes: A primer.* W. H. Freeman & Company, San Francisco, Chapter 6.

Eiby, George A. 1980. *Earthquakes.* Van Nostrand Reinhold Company, New York. 209 pp.

We are indebted to Charles G. Sammis, Department of Geological Sciences at the University of Southern California, for his assistance in preparing this exercise.