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Earthquake Hazards and Human Risks

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OBJECTIVES

A. Experiment with models to determine how earthquake damage to buildings is related to the Earth materials on which they are constructed. Apply your experimental results to evaluate earthquake hazards and human risks in San Francisco.

B. Graph seismic data to construct and evaluate travel time curves for P-waves, S-waves, and L-waves. Use seismograms and your travel time curves to locate the epicenter of an earthquake.

C. Analyze and evaluate active faults using remote sensing and geologic maps.

D. Interpret seismograms to infer relative movements along the New Madrid Fault System within the North American Plate.

E. Explore real-time earthquake data, hazards, and impacts on humans using resources from the Internet.

MATERIALS

Pencil, eraser, laboratory notebook, ruler, calculator, drafting compass, several coins, a small plastic or paper cup containing dry sediment (fine sand, sugar, or salt), and a wash bottle.

INTRODUCTION

Earthquakes are shaking motions and vibrations of the Earth caused by large releases of energy that accompany volcanic eruptions, explosions, and movements of Earth's bedrock along fault lines. News reports usually describe an earthquake's **epicenter**, which is the point on Earth's surface (location on a map) directly above the **focus** (underground origin of the earthquake, in bedrock). The episodic releases of energy that occur along fault lines strain the bedrock like a person jumping on a diving board. This strain produces elastic waves of vibration and shaking called **seismic waves** (earthquake waves). Seismic waves originate at the earthquake's focus and travel in all directions through the rock body of Earth and along Earth's surface. The surface seismic waves travel in all directions from the epicenter, like the rings of ripples (small waves) that form when a stone is cast into a pond. In fact, people who have experienced strong surface seismic waves report that they saw and felt wave after wave of elastic motion passing by like the above-mentioned ripples on a pond. These waves are strongest near the epicenter and grow weaker with distance from the epicenter. For example, when a strong earthquake struck Mexico City in 1985, it caused massive property damage and 9500 deaths in a circular area radiating about 400 km (250 mi) in every direction from the city. By the time these same surface seismic waves of energy had traveled 3200 km to Pennsylvania, they were so weak that people could not even feel them passing beneath their feet. They did, however, cause water levels in wells and swimming pools to fluctuate by as much as 12 cm. They also were recorded by earthquake-detecting instruments called *seismographs*. Therefore, although most damage from an earthquake usually occurs close to its epicenter, seismographs can detect the earthquake's waves of energy even when they travel through Earth's rocky body or along Earth's surface to locations thousands of kilometers away from the epicenter.

Fault motions (movements of Earth's crust along breaks in the rocks) are the most common source of earthquakes felt by people. These motions can occur along faults that do not break the Earth's surface or along faults that do break the Earth's surface. Fault motions at Earth's surface can directly cause *hazards* such as the destruction of buildings, breakage of pipes and electric lines, development of open fissures in the soil, change in the course of streams, and generation of tsunamis (destructive ocean waves, generally 1–10 m high, that devastate coastal environments). However, *all* earthquakes cause some degree of vibration and shaking of the Earth, which can also cause most of the above-mentioned hazards.

Therefore people who live where strong earthquakes occur are at *risk* for experiencing personal injury, property damage, and disruption of their livelihoods and daily routines. Geologists study seismic waves, map active faults, determine the nature of earthquake-induced hazards, assess human risk where such hazards occur, and assist in the development of government policies related to public safety in earthquake-prone regions.

PART A: SIMULATE EARTHQUAKE HAZARDS TO ESTIMATE RISKS

Geoscientists and engineers commonly simulate earthquakes in the laboratory to observe their effects on models of construction sites, buildings, bridges, and so on. Now is your turn to give it a try. Start by making simple models of buildings constructed in dry, uncompacted sediment (Model 1) and moist, compacted sediment (Model 2). Then simulate earthquakes and observe what happens to them.

Questions

Obtain a small plastic or paper cup. Fill it three-quarters full with a dry sediment like sand, dirt, salt, or sugar. Place several coins in the sediment so they resemble vertical walls of buildings constructed on a substrate of uncompacted sediment (as in Figure 1). This is Model 1. Observe what happens to Model 1 when you *simulate an earthquake* by tapping the cup on a table top while you also rotate it counterclockwise.

1. What happened to the vertically positioned coins in the uncompacted sediment of Model 1 when you simulated an earthquake?

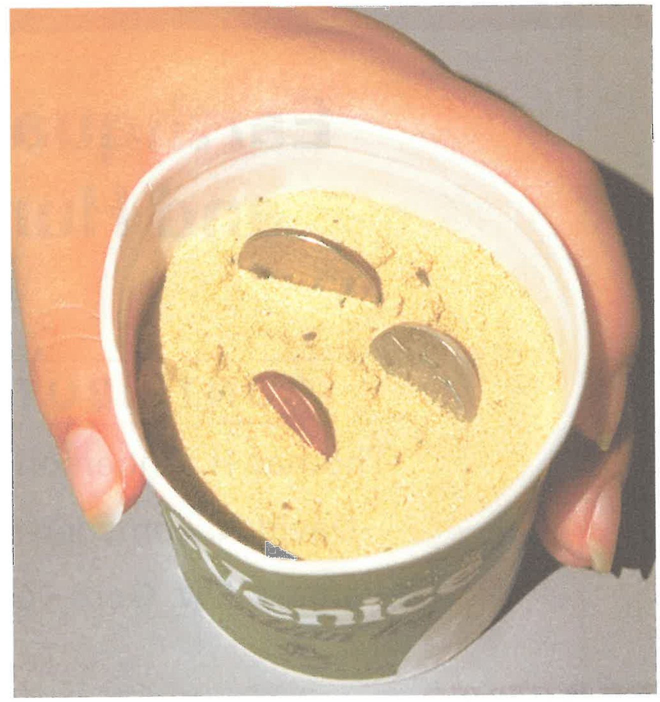

FIGURE 1 Photograph of Model 1 being subjected to a simulated earthquake.

Now make Model 2. Remove the coins from Model 1, and add a small bit of water to the sediment in the cup so that it is moist (but not soupy). Press down on the sediment in the cup so that it is well compacted, and then place the coins into this compacted sediment just as you placed them in Model 1 earlier. *Simulate an earthquake* as you did for Model 1, and then answer Questions 2 and 3.

2. What happened to the vertically positioned coins in the compacted sediment of Model 2 when you simulated an earthquake?
3. Based on your experimental Models 1 and 2, which kind of Earth material is more hazardous to build on in earthquake-prone regions: compacted sediment or uncompacted sediment? (Justify your answer by citing evidence from your experimental models.)
4. Consider the moist, compacted sediment in Model 2. Do you think this material would become *more* hazardous to build on, or *less* hazardous to build on, if it became totally saturated with water during a rainy season? (To find out and justify your answer, design and conduct another experimental model of your own. Call it Model 3.)
5. Write a statement that summarizes how water in a sandy substrate beneath a home can be beneficial or hazardous. Justify your reasoning with reference to your experimental models.

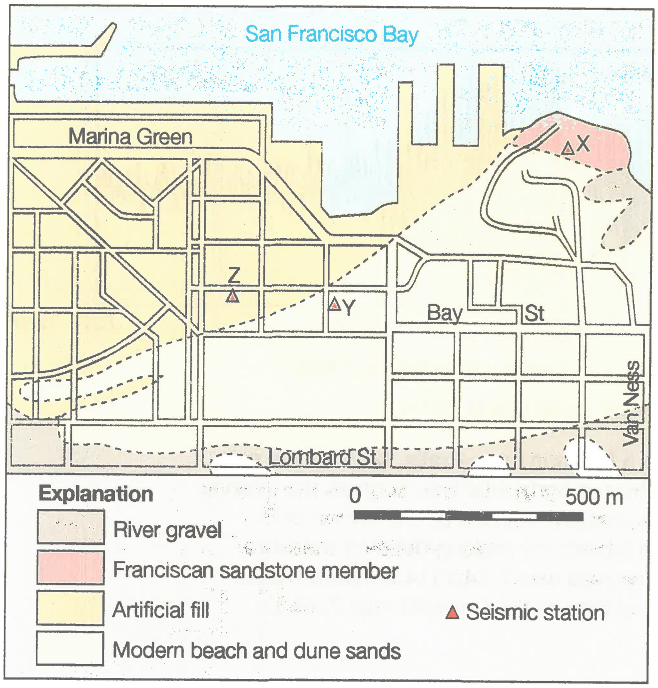

FIGURE 2 Map of the nature and distribution of Earth materials on which buildings and roads have been constructed for a portion of San Francisco, California. (Courtesy of U.S. Geological Survey)

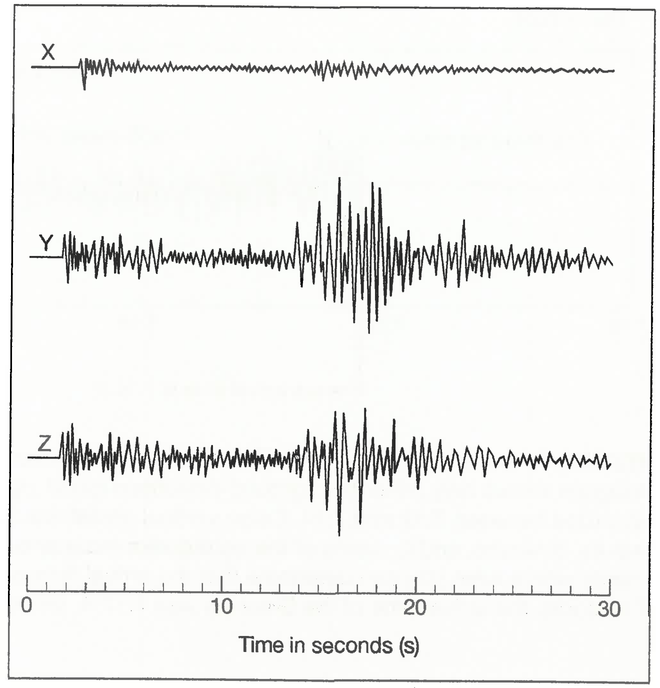

FIGURE 3 Seismograms recorded at Stations **X, Y,** and **Z,** for a strong (Richter Magnitude 4.6) aftershock of the Loma Prieta, California, earthquake. During the earthquake, little damage occurred at **X,** but significant damage to houses occurred at **Y** and **Z.** (Courtesy of U.S. Geological Survey)

San Francisco is located in a tectonically active region, so it occasionally experiences strong earthquakes. Figure 2 is a map showing the kinds of Earth materials upon which buildings have been constructed in a portion of San Francisco. These materials include hard compact Franciscan Sandstone, uncompacted beach and dune sands, river gravel, and artificial fill. The artificial fill is mostly debris from buildings destroyed in the great 1906 earthquake that reduced large portions of the city to blocks of rubble. Also note that three locations have been labeled **X, Y,** and **Z** on Figure 2. Imagine that you have been hired by an insurance company to assess what risk there may be in buying newly constructed apartment buildings located at **X, Y,** and **Z** on Figure 2. Your job is to infer whether the risk of property damage during strong earthquakes is **low** (little or no damage expected) or **high** (damage can be expected). All that you have as a basis for reasoning is Figure 2 and knowledge of your experiments with models in Questions 1–4.

6. What is the risk at location **X?** Why?
7. What is the risk at location **Y?** Why?
8. What is the risk at location **Z?** Why?

On October 17, 1989, just as Game 3 of the World Series was about to start in San Francisco, a strong earthquake occurred at Loma Prieta, California, and shook the entire San Francisco Bay area. Seismographs at locations **X, Y,** and **Z** (see Figure 2) recorded the shaking, and the resulting seismograms are shown in Figure 3. Earthquakes are recorded on the seismograms as deviations (vertical zigzags) from a flat, horizontal line. Thus, notice that much more shaking occurred at locations **Y** and **Z** than at location **X.**

9. The Loma Prieta earthquake caused no significant damage at location **X,** but there was moderate damage to buildings at location Y and severe damage at location **Z.** Explain how this damage report compares to your predictions of risk in Questions 6, 7, and 8.
10. The Loma Prieta earthquake shook all of the San Francisco Bay region. Yet Figure 3 is evidence that the earthquake had very different effects on properties located only 600 m apart. Explain how the kind of substrate (uncompacted vs. firm and compacted) on which buildings are constructed influences how much the buildings are shaken and damaged in an earthquake.

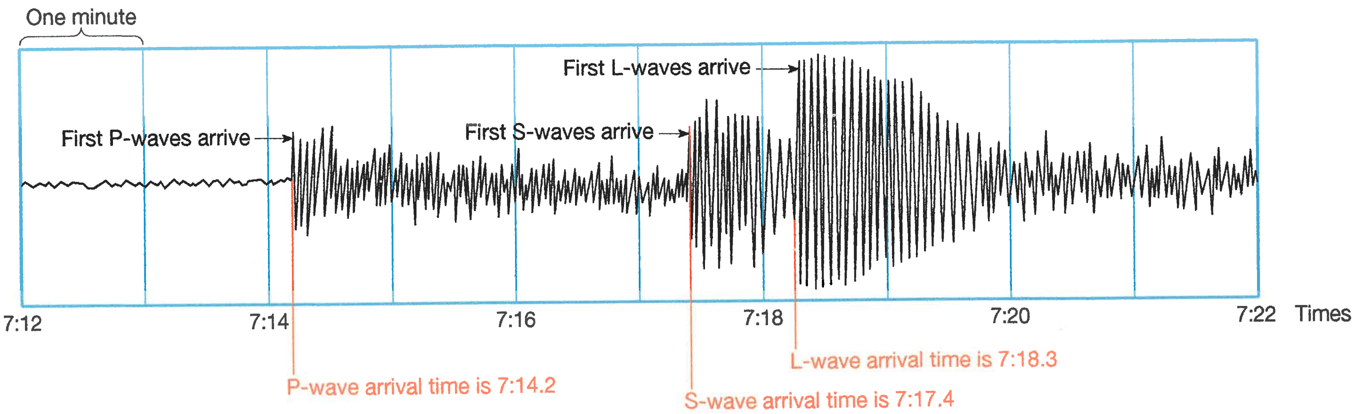

FIGURE 4 Seismogram of a New Guinea earthquake recorded at a location in Australia. Most of the seismogram shows only minor background deviations (short zigzags) from a horizontal line, such as the interval recorded between 7:12 and 7:14. Large vertical deviations indicate motions caused by the arrival of P-waves, S-waves, and L-waves of the earthquake (note arrows with labels). By making detailed measurements with a ruler, you can determine that the arrival time of the P-waves was 7:14.2 (14.2 minutes past 7 o'clock), the arrival time of the S-waves was 7:17.4, and the arrival time of the L-waves was 7:18.3.

11. Imagine that you are a member of the San Francisco City Council. What actions could you propose to **mitigate** (decrease the probability of) future earthquake hazards such as the damage that occurred at locations **Y** and **Z** in the Loma Prieta earthquake?

PART B: GRAPHING SEISMIC DATA AND LOCATING THE EPICENTER OF AN EARTHQUAKE

An earthquake produces three main types of seismic waves that radiate from its focus/epicenter at different rates. Seismographs are instruments used to detect these seismic waves and produce a **seismogram**—a record of seismic wave motions obtained at a specific recording station (Figure 4).

Seismograms can detect and record several types of *body waves*, which are seismic waves that travel through Earth's interior (rather than along its surface) and radiate in all directions from the focus. Two of these body waves are used to locate earthquake epicenters:

- **P-waves:** *P* for primary, because they travel fastest and arrive at seismographs first. (They are compressional, or "push-pull" waves.)
- **S-waves:** *S* for secondary, because they travel more slowly and arrive at seismographs after the P-waves. (They are perpendicular, shear, or "side-to-side" waves.)

Seismographs also detect the surface seismic waves, called **L-waves** or *Love waves* (named for A. E. H. Love, who discovered them). L-waves travel along Earth's surface (a longer route than the body waves) and thus are recorded after the S-waves and P-waves arrive at the seismograph.

Figure 4 is a seismogram recorded at a station located in Australia. Seismic waves arrived there from an earthquake epicenter located 1800 kilometers (1125 miles) away in New Guinea. Notice that the seismic waves were recorded as deviations (vertical zigzags) from the nearly horizontal line of normal background vibrations. Thus, the first pulse of seismic waves was P-waves, which had an **arrival time** of 7:14.2 (i.e., 14.2 minutes after 7:00). The second pulse of seismic waves was the slower S-waves, which had an arrival time of 7:17.4. The final pulse of seismic waves was the L-waves that traveled along Earth's surface, so they did not begin to arrive until 7:18.3. The earthquake actually occurred at the New Guinea epicenter at 7:10:23 (10 minutes and 23 seconds after 7:00) Greenwich Mean Time, which can be written as 7:10.4. Therefore the **travel time of the main seismic waves** (to go 1800 km) was 3.8 minutes for P-waves (7:14.2 minus 7:10.4), 7.0 minutes for S-waves (7:17.4 minus 7:10.4), and 7.9 minutes for L-waves (7:18.3 minus 7:10.4).

Notice the seismic data provided in Figure 5 for 11 recording stations where seismograms were recorded after the same New Guinea earthquake (at 3° North latitude and 140° East longitude). The **distance from epicenter** (surface distance between the recording station and the epicenter) and travel time of main seismic waves are provided for each

Data Table

Recording Station (Seismograph location)	Distance to Epicenter (kilometers)	Travel Time of Main Seismic Waves (minutes)
1. Australia (Figure 4)	1800	3.8
	1800	7.0
	1800	7.9
2. Port Moresby, New Guinea	950	2.2
	950	4.0
	950	4.1
3. Darwin, Australia	1500	3.2
	1500	6.0
	1500	6.6
4. Guam	1950	4.0
	1950	7.4
5. Brisbane, Australia	2860	5.7
	2860	10.0
6. Noumea, New Caledonia	3370	6.3
	3370	14.8
7. Lembang, Java	3720	6.8
	3720	12.0
8. Nhatrang, Vietnam	3960	7.0
	3960	17.4
9. Matsushiro, Japan	4460	7.6
	4460	13.5
	4460	19.6
10. Vladivostok, Russia	5230	8.6
	5230	22.9
11. Chittagong, Pakistan	6080	9.5
	6080	17.0
	6080	26.7

GRAPH OF SEISMIC WAVE TRAVEL TIME VS. DISTANCE

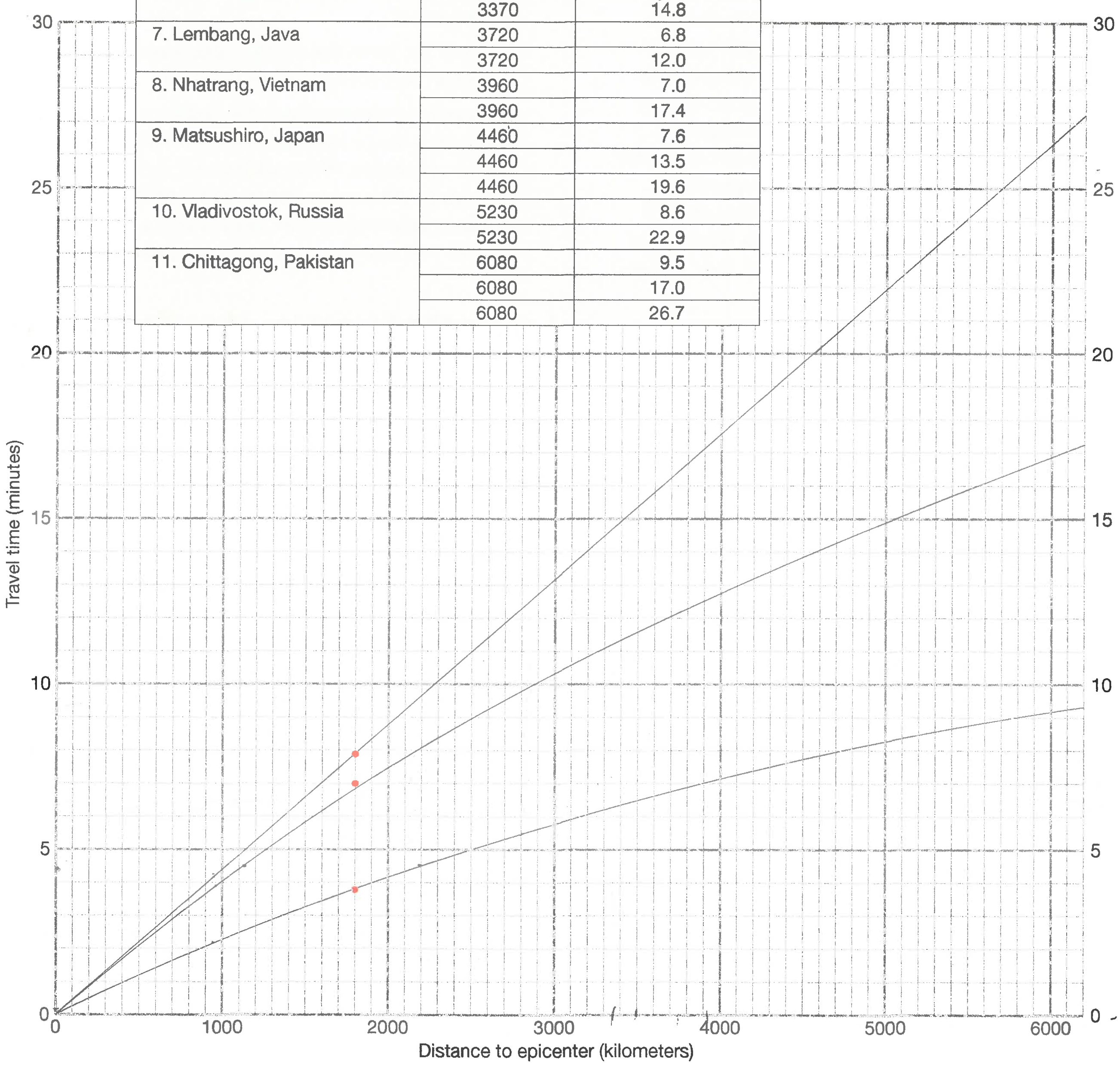

FIGURE 5 Seismic wave data for an earthquake that occurred in New Guinea (at 3° North latitude and 140° East longitude) at Greenwich Mean Time of 7 hours, 10 minutes, 23 seconds (7:10.4). The travel time of a main seismic wave is the time interval between when the earthquake occurred in New Guinea and when that wave first arrived at a recording location. The surface distance is the distance between the recording location and the earthquake epicenter. Graph is for plotting points that represent the travel time of each main seismic wave at each location versus the surface distance that it traveled.

recording station. Notice that the data from most of the recording stations includes travel times for all three main kinds of seismic waves (P-waves, S-waves, and L-waves). However, instruments at some locations recorded only one or two kinds of waves. Location 1 is the Australian recording station where the seismogram in Figure 4 was obtained.

Questions

12. On the graph paper provided at the base of Figure 5, *plot points in pencil to show the travel time of each main seismic wave in relation to its distance from the epicenter* (when recorded on the seismogram at the recording station). For example, the data for location 1 (obtained from Figure 4) have already been plotted as red points on Figure 5. Recording station 1 was located 1800 km from the earthquake epicenter and the main waves had travel times of 3.8 minutes, 7.0 minutes, and 7.9 minutes. Plot points in pencil for data from all of the remaining recording stations, and then examine the graph.

Notice that your points do not produce a *random pattern*. They fall in *discrete paths* close to the three narrow black lines (or curves) already drawn on the graph. These black lines (or curves) were formed by plotting many thousands of points from hundreds of earthquakes, exactly as you just plotted your points. Explain why you think that your points, and all of the points from other earthquakes, occur along three discrete lines (or curves).

13. Study the three discrete, narrow black lines (or curves) of points in Figure 5. Label the line (curve) of points that represents travel times of the P-waves. Label the line or curve that connects the points representing travel times of the S-waves. Label the line or curve that connects the points representing travel times of the L-waves. Why is the S-wave curve steeper than the P-wave curve?

14. Why do the L-wave data points form a straight line whereas data points for P-waves and S-waves form curves? (*Hint:* The curved lines are evidence of how the physical environments and rocks deep inside Earth are different from the physical environments and rocks just beneath Earth's surface.)

15. Notice that the origin on your graph (travel time of zero and distance of zero) represents the location of the earthquake epicenter and the start of the seismic waves. The time interval between first arrival of P-waves and first arrival of S-waves at the same recording station is called the **S-minus-P time interval.** How does the S-minus-P time interval change with distance from the epicenter?

16. Imagine that an earthquake occurred this morning. The first P-waves of the earthquake were recorded at a recording station in Houston at 6:12.6 a.m. and the first S-waves arrived at the same Houston station at 6:17.1 a.m. Use Figure 5 to determine an answer for each question below.

a. What is the S-minus-P time interval of the earthquake?

b. How far from the earthquake's epicenter is the Houston recording station located?

c. You have determined the distance (radius of a circle on a map) between Houston and the earthquake epicenter. What additional data would you require to determine the location of the earthquake's epicenter (point on a map), and how would you use the data to locate the epicenter?

Locate the Epicenter of an Earthquake

See if you can use the travel time curves in Figure 5 to locate the epicenter (point on a map) of the earthquake that produced the seismograms in Figure 6. These seismograms were recorded at stations in Alaska, North Carolina, and Hawaii.

Questions

17. Estimate, to the nearest tenth of a minute, the times that P-waves and S-waves first arrived at each recording station (seismograph location) in Figure 6. Then, subtract P from S to get the S-minus-P time interval:

	First P arrival	First S arrival	S-minus-P
Sitka, AK	_____	_____	_____
Charlotte, NC	_____	_____	_____
Honolulu, HI	_____	_____	_____

18. Using the S-minus-P time intervals and Figure 5, determine the distance from epicenter (in kilometers) for each recording station.

Sitka, AK _____ kilometers

Charlotte, NC _____ kilometers

Honolulu, HI _____ kilometers

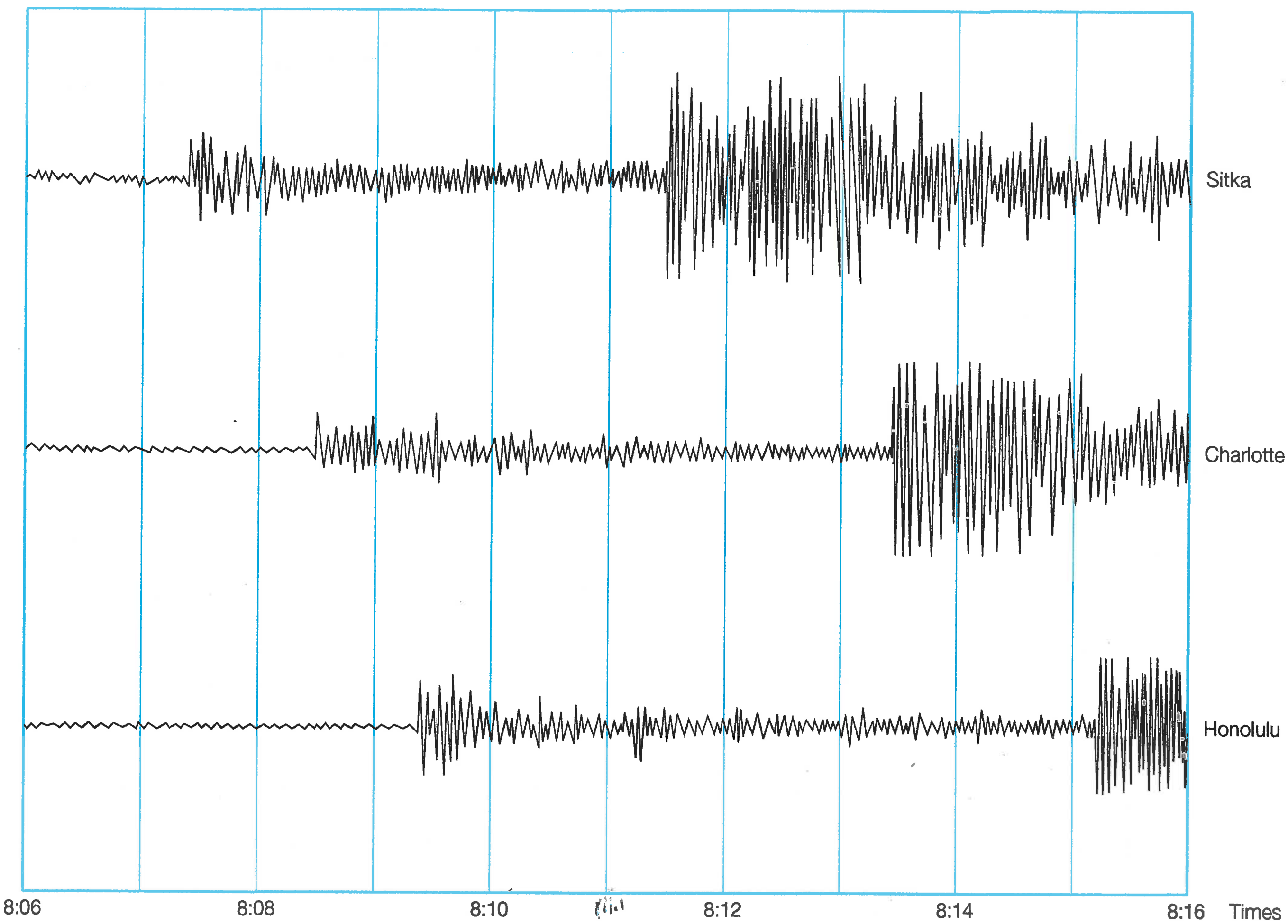

FIGURE 6 Seismograms for an earthquake recorded at three different locations in Alaska, North Carolina, and Hawaii. Times have been standardized to Charlotte, North Carolina, to simplify comparison.

19. Next, find the earthquake's epicenter using the distances just obtained.

a. First use the geographic coordinates below to locate and mark the three recording stations on the world map in Figure 7.

Sitka, AK: 57°N latitude, 135°W longitude

Charlotte, NC: 35°N latitude, 81°W longitude

Honolulu, HI: 21°N latitude, 158°W longitude

b. Use a drafting compass to draw a circle around each recording station. Make the radius of each circle equal to the *distance from epicenter* determined for the station in Question 18. (Use the scale on Figure 7 to set this radius on your drafting compass.) The circles you draw should intersect approximately at one point on the map. This point is the epicenter. (If the three circles do not quite intersect at a single point, then find a point that is equidistant from the three edges of the circles, and use this as the epicenter.) Record the location of the earthquake epicenter:

N Latitude ______ W Longitude ______

20. What is the name of a major fault that occurs near this epicenter?

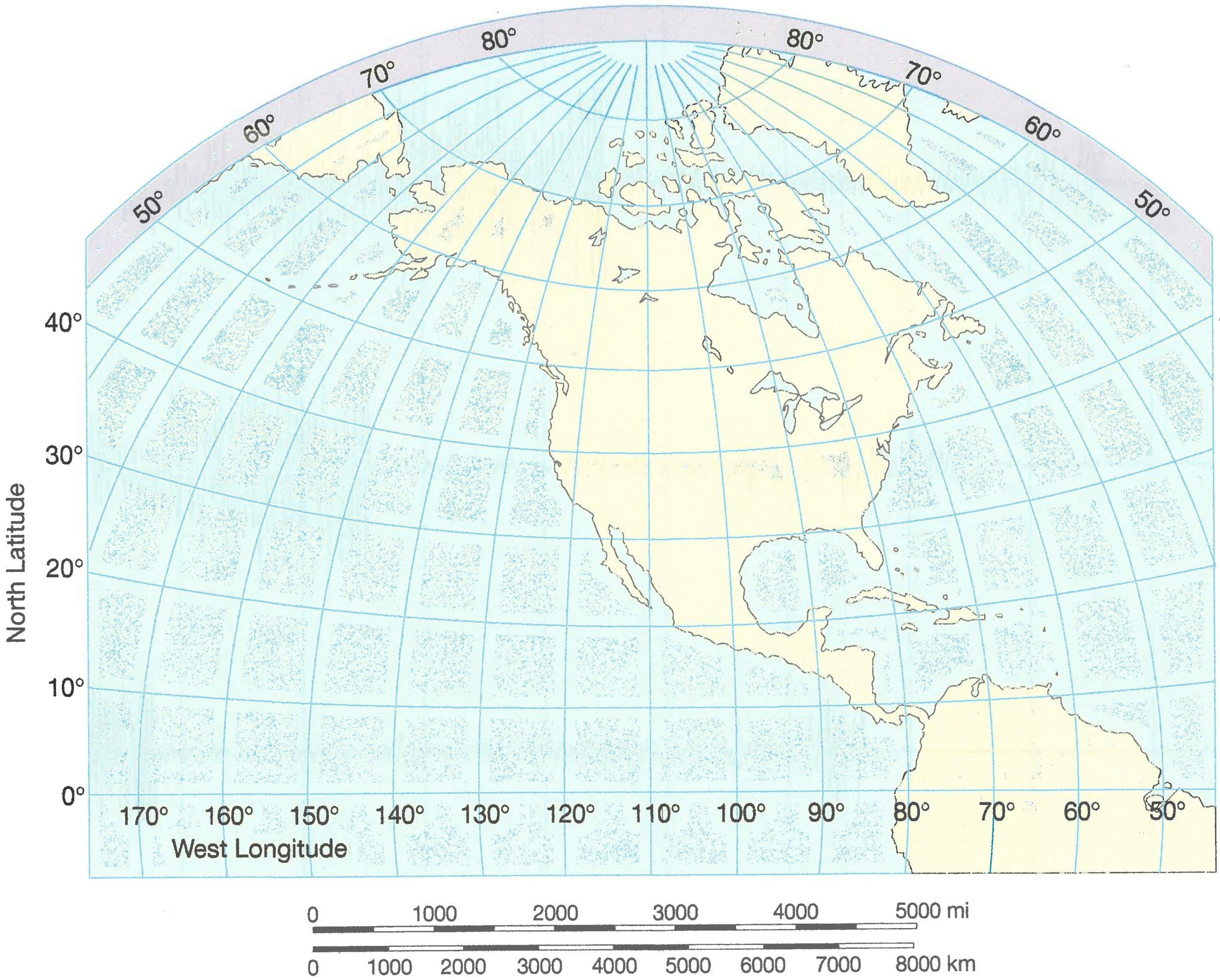

FIGURE 7 Map of Earth, for use in plotting data and locating the earthquake's epicenter.

PART C: ANALYSIS OF ACTIVE FAULTS USING AERIAL PHOTOGRAPHS

There are many faults that can be imaged, photographed, mapped, and studied where they break Earth's surface. Some of these faults are **active faults,** meaning that they can move and generate earthquakes at the present time.

Examine the aerial photograph of a portion of southern California (Figure 8) for evidence of faults and fault motions. Notice the roads, small streams, and fine features of the landscape. Also notice that the figure shows a portion of the San Andreas Fault, which is a tectonic plate boundary separating the Pacific Plate from the North American Plate.

Questions

21. Geologists have inferred that the San Andreas Fault is an active fault and that the blocks of rock on either side of the fault are moving in the directions indicated with half-arrows.

a. What evidence, visible in this photograph, could you use to suggest that this fault is both active and moving relative to the arrows? Explain your reasoning.

b. How much has the San Andreas Fault offset the present-day channel of Wallace Creek?

c. Is the San Andreas Fault a left-lateral fault or a right-lateral fault? Explain.

22. How wide is the San Andreas Fault (tectonic plate boundary) here?

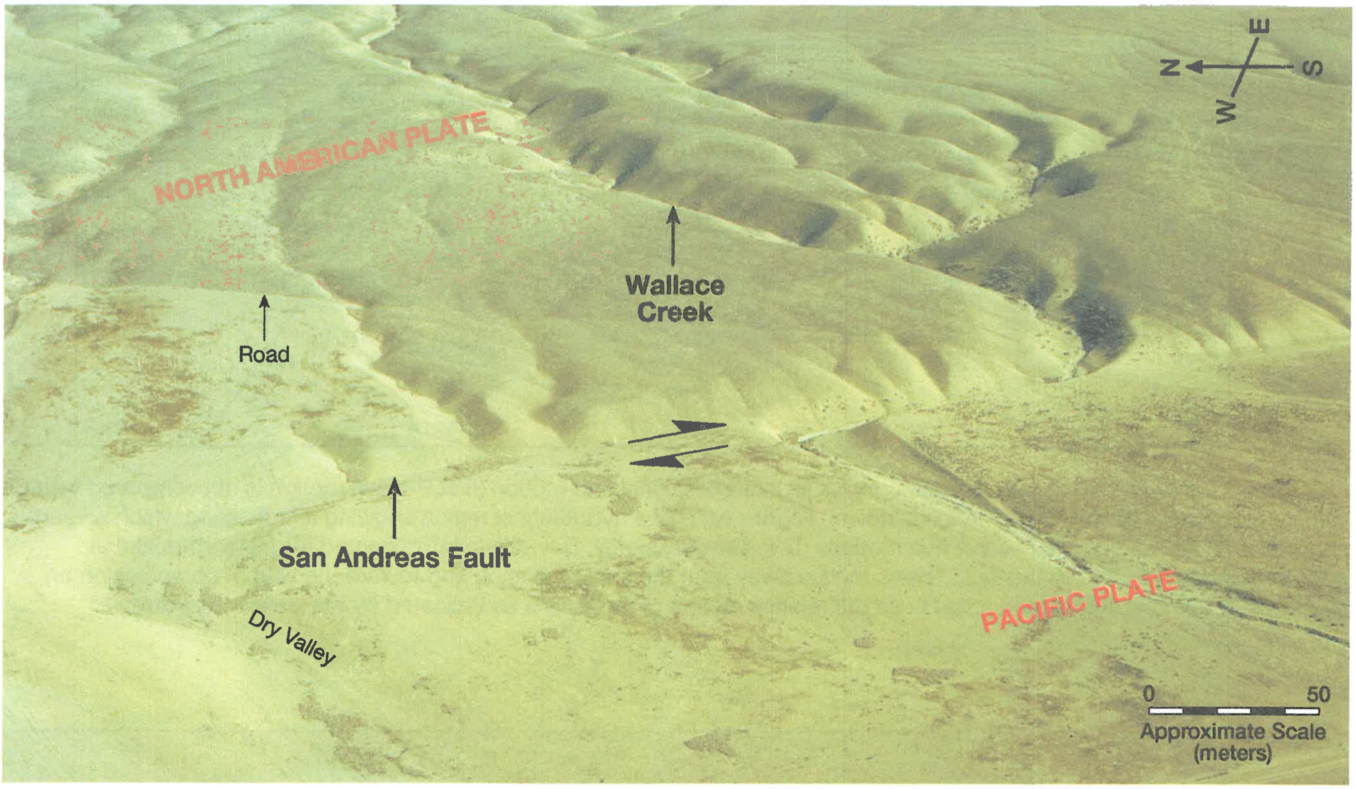

FIGURE 8 Aerial photograph of a portion of the San Andreas Fault (a tectonic plate boundary) at Wallace Creek, Carrizo Plain, southern California. (Photo by Randall Marrett, University of Texas, Austin)

23. Notice the small dry valley in the lower-left part of the photograph. Infer how this valley may have formed.

PART D: DETERMINING RELATIVE MOTIONS ALONG THE NEW MADRID FAULT ZONE

The relative motions of blocks of rock on either side of a fault zone can be determined by mapping the way the pen on a seismograph moved (up or down on the seismogram) when P-waves first arrived at various seismic stations adjacent to the fault. This pen motion is called **first motion** and represents the reaction of the P-wave to dilation (pulling rocks apart) or compression (squeezing rocks together) as observed on seismograms (see Figure 9, left).

If the first movement of the P-wave was up on a seismogram, then that recording station (where the seismogram was obtained) experienced compression during the earthquake. If the first movement of the P-wave was down on a seismogram, then that recording station was dilational during the earthquake. What was the first motion at all of the seismic stations in Figure 3? (Answer: The first movement of the pen was up for each P-wave, so the first motion at all three sites was compressional.)

By plotting the first motions observed at recording stations on both sides of a fault that has experienced an earthquake, a picture of the relative motions of the fault emerges. For example, notice that the first motions observed at seismic stations on either side of a hypothetical fault are plotted in relation to the fault in Figure 9 (right side). The half-arrows indicate how motion proceeded away from seismic stations where dilation was recorded and toward seismic stations where compression was recorded (for each side of the fault). So the picture of relative motion along this fault is that Block **X** is moving southeast and Block **Y** is moving northwest. Now study a real example using Figures 10 and 11.

The New Madrid Fault System is located within the *Mississippi Embayment*, a basin filled with Mesozoic and Cenozoic rocks that rest unconformably on (and are surrounded by) Paleozoic and Precambrian rocks (see Figure 11). Faults of the New Madrid System are not visible on satellite images and photographs, because

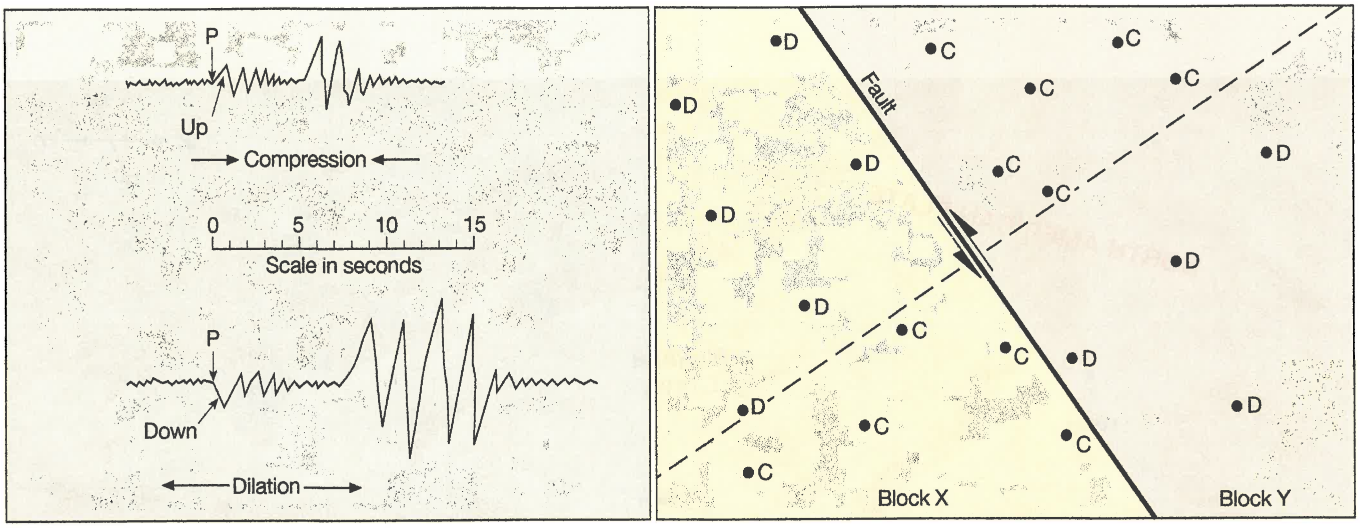

FIGURE 9 **Left**—Sketch of typical seismograms for compressional first motion (first P-wave motion is up) compared with dilational first motion (first P-wave motion is down). **Right**—Map of a hypothetical region showing a fault along which an earthquake has occurred, and the P-wave first motions (C = compressional, D = dilational) observed for the earthquake at seismic stations adjacent to the fault. Stress moves away from the field of dilation and toward the field of compression on each side of the fault (large open arrows), so the relative motion of the fault is as indicated by the smaller half-arrows.

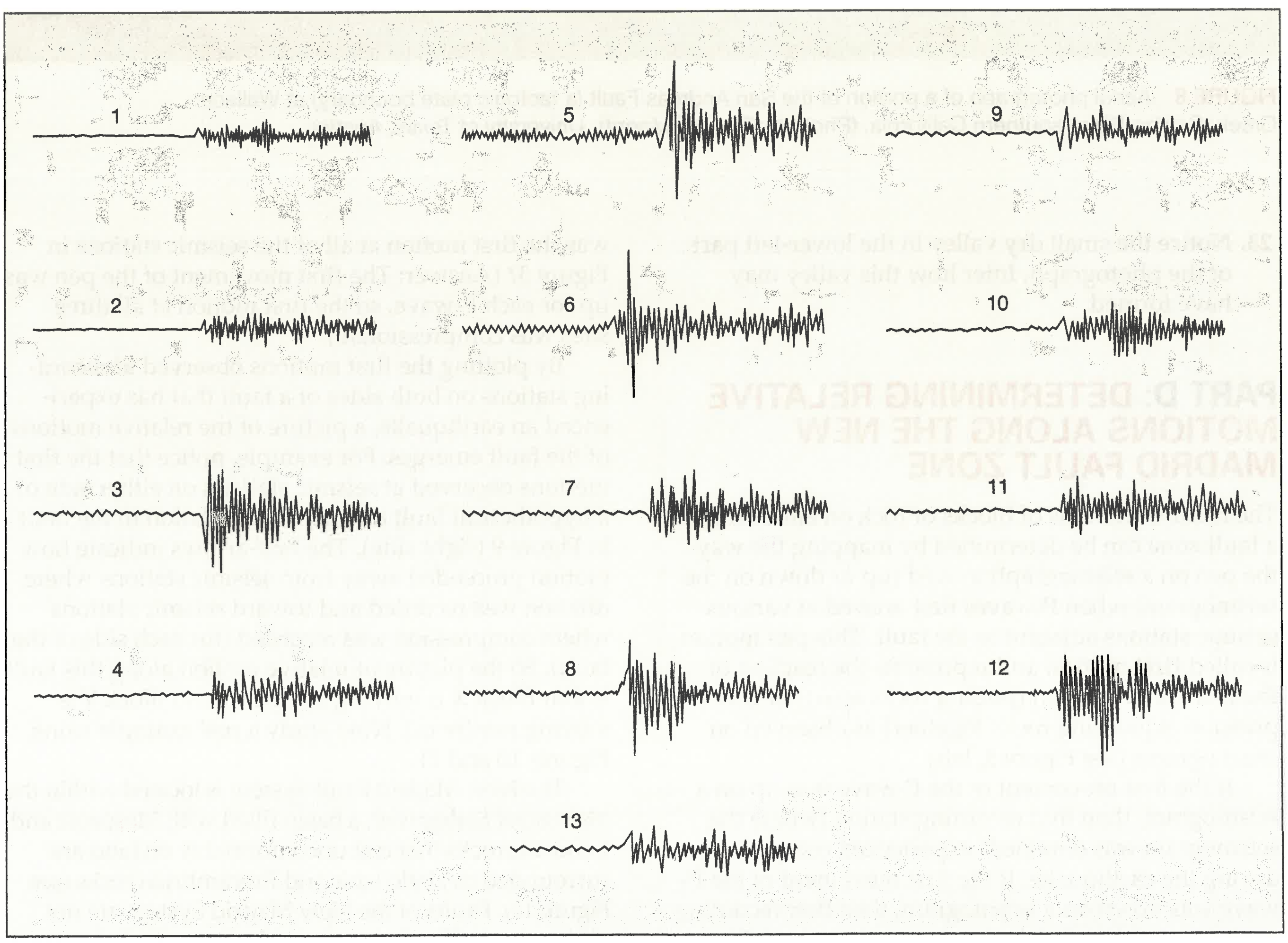

FIGURE 10 Seismograms from 13 numbered seismic stations in the Mississippi Embayment after an earthquake that occurred in the New Madrid Fault System. Numbers in this figure correspond to the numbered sites on the map in Figure 11.

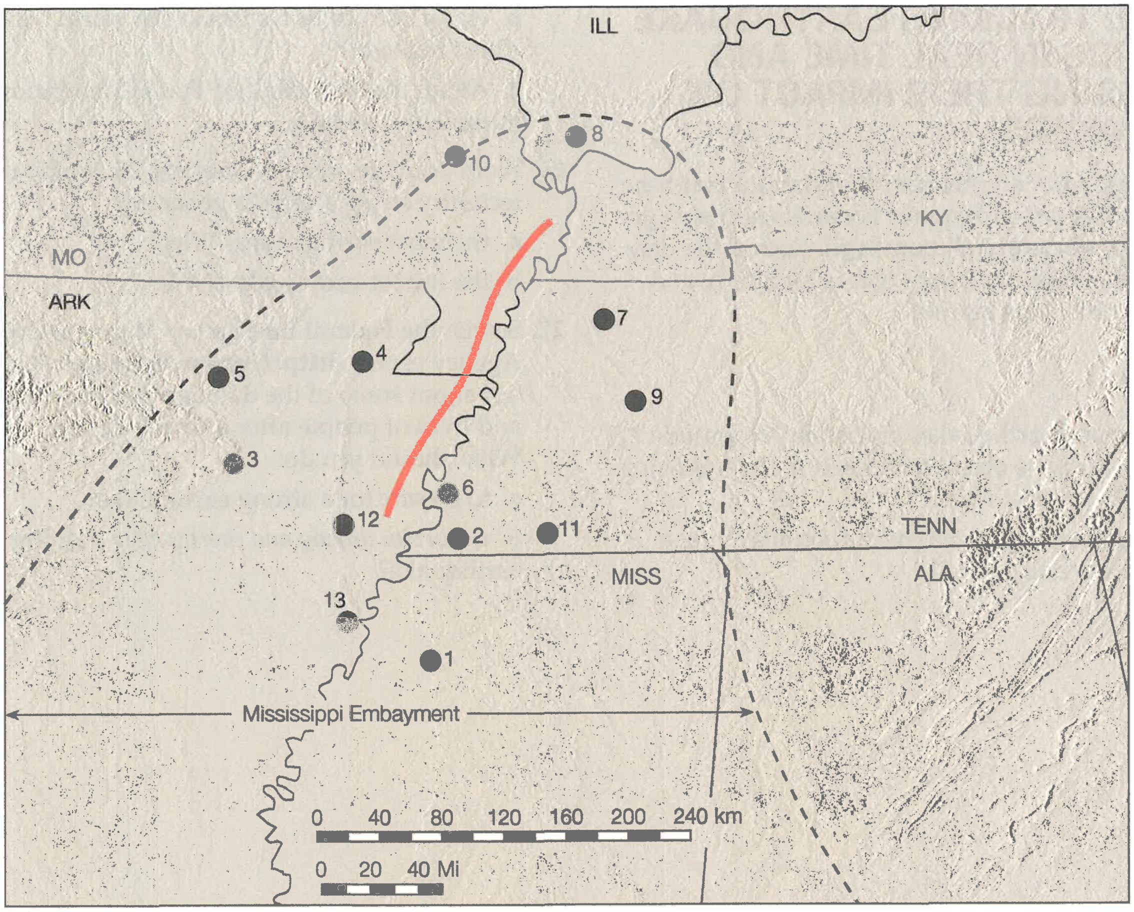

FIGURE 11 Map of a portion of the Mississippi Embayment showing the generalized surface geology, location (in red) of the main fault of the New Madrid (Blind) Fault System, numbered seismic stations (as in Figure 10), and state boundaries.

they are **blind faults** (faults that do not break Earth's surface). These blind faults occur in the Paleozoic and Precambrian rocks that are buried beneath approximately a kilometer of Mesozoic and Cenozoic rocks.

The main fault of the New Madrid System is plotted in red on Figure 11. It is well known, because a series of strong earthquakes occurred along it in 1811 and 1812. One of these earthquakes was the strongest earthquake ever recorded in North America, and the potential for more strong earthquakes here is a lingering hazard. The locations of 13 seismic stations are also plotted on Figure 11. Seismograms obtained at these stations (after an earthquake along the New Madrid Fault System) are provided in Figure 10.

Question

24. Analyze the seismograms in Figure 10 to determine if their P-wave first motions indicate compression or dilation (refer to Figure 9 as needed). Plot this information on Figure 11 by writing a *C* beside the stations where compression occurred and a *D* beside the stations where dilation occurred. When you have finished plotting these letters, draw half-arrows on Figure 11 to indicate the relative motions of the blocks of rock on either side of the main fault. Does the main fault have a right-lateral motion or a left-lateral motion? Explain.

Unlike most major active fault zones that occur at plate boundaries (such as the San Andreas Fault), the New Madrid Fault System is an active and hazardous system of faults that occurs *within* the North American Plate. Intraplate stresses are apparently causing adjustments along these blind faults and the potential for more earthquakes that place humans at risk.

PART E: TRACKING EARTHQUAKE HAZARDS IN REAL TIME AND ASSESSING THEIR IMPACT ON RISK TAKERS

Find and explore Internet sites that contain real-time information about earthquake hazards and risks (go to **http://www.prenhall.com/agi**). Record the date and time that you conducted this exploration, and proceed to the items below.

Questions

25. How many earthquakes of Richter Magnitude 2.5 or greater have occurred in each of the following areas in the past week?

a. Southern California (from motions along a plate boundary):

b. Hawaii (from tectonism at the world's most active hot spot):

c. Along the New Madrid Fault Zone (from intraplate stresses):

26. From your answers in Question 25, which plate tectonic setting seems to generate:

a. the most earthquakes? Why?

b. the fewest earthquakes? Why?

27. Search the Federal Emergency Management Agency server (**http://www.fema.gov/**) to find out about some of the damage done to properties and lives of people after a strong earthquake. What should *you* do:

a. to *prepare* for a strong earthquake?

b. to *survive during and shortly after* a strong earthquake?