EXERCISE 2

EARTHQUAKE MAGNITUDE AND INTENSITY

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Supplies Needed

• calculator
• metric ruler

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PURPOSE

Exercise 1 introduced many of the fundamental concepts of earthquakes, and this exercise will add two more important concepts: earthquake magnitude and intensity. Both magnitude and intensity are expressions of the amount of energy released when a fault ruptures. Scientists are interested in measuring seismic energy in order to categorize earthquakes and to better understand tectonic processes. Society is interested in the strength of past and future earthquakes in order to assess and predict damage and loss of life. The following exercise will use data from the 1994 Northridge earthquake to illustrate the method for calculating Richter magnitude and for mapping seismic-shaking intensity.

MAGNITUDE

Magnitude is a measurement of the energy released by an earthquake. The first earthquake-magnitude scale was the *Richter scale,* devised by Charles F. Richter, a seismologist at the California Institute of Technology. The Richter scale is based on the amplitude of seismic waves – the stronger the earthquake, the stronger the seismic vibrations it causes. The Richter magnitude of an earthquake is expressed as a decimal number, such as 6.7. The most important thing to remember about Richter magnitude is that it is a logarithmic scale, meaning that an increase of *one* in magnitude corresponds to a factor of *ten* increase in the amplitude of ground motion. For example, a magnitude 6.7 earthquake causes shaking 10 times greater in amplitude than a magnitude 5.7 earthquake and 100 times greater than a magnitude 4.7 earthquake.

Mathematically, an earthquake of magnitude x results in seismic waves with amplitudes proportional to 10^x. The actual seismic-wave amplitude at a particular site depends on the distance of the site from the earthquake epicenter, the depth of the earthquake, and local near-surface conditions. Example 2.1 shows you how to compare the shaking that results from earthquakes with different magnitudes.

Magnitude and Intensity

Example 2.1.

Compare the seismic shaking produced by a magnitude 8.2 earthquake with the shaking from a magnitude 6.7 earthquake?

When we say that the amplitude of seismic waves (A) from an earthquake of magnitude x are proportional to 10^x, that is equivalent to saying:

$$A_{(M=x)} = k * 10^x$$

where k is an arbitrary constant. Thus:

$$A_{(M=8.2)} = k * 10^{8.2}$$

and:

$$A_{(M=6.7)} = k * 10^{6.7}$$

When asked to compare the shaking produced by two earthquakes, you are being asked to solve for the ratio of the two earthquake amplitudes, in this case $A_{(M=8.2)} \div A_{(M=6.7)}$:

$$A_{(M=8.2)} \div A_{(M=6.7)} = k * 10^{8.2} \div k * 10^{6.7}$$

$$k * 10^{8.2} \div k * 10^{6.7} = 10^{8.2} \div 10^{6.7} = 10^{(8.2-6.7)} = 10^{1.5}$$

thus: $\qquad A_{(M=8.2)} \div A_{(M=6.7)} = 10^{1.5} = 31.6$

Answer: A magnitude 8.2 earthquake creates shaking 31.6 times more greater in amplitude than a magnitude 6.7 earthquake.

1) The 1906 San Francisco earthquake had a magnitude of about 8.3. The 1989 Loma Prieta earthquake that struck San Francisco had a magnitude of 7.1. How much greater was the shaking in 1906 earthquake compared with the shaking in 1989?

2) How much greater was the shaking during the 1906 San Francisco earthquake than the shaking during a magnitude 4.0 tremor?

The method for determining the magnitude of an earthquake is illustrated in Figure 2.1 below. Richter magnitude (M) is a function of the amplitude of the largest wave on a seismogram and the distance from the recording station to the epicenter (measured either directly in kilometers or indirectly as the S–P lag time; see Exercise 1). On Figure 2.1, the magnitude is determined by connecting the maximum wave amplitude (85 mm with proper scaling of the seismogram) with the epicentral distance (300 km, or 34 sec S–P lag). The magnitude of the earthquake shown is the intersection of that line with the magnitude axis of the diagram at M=6.0.
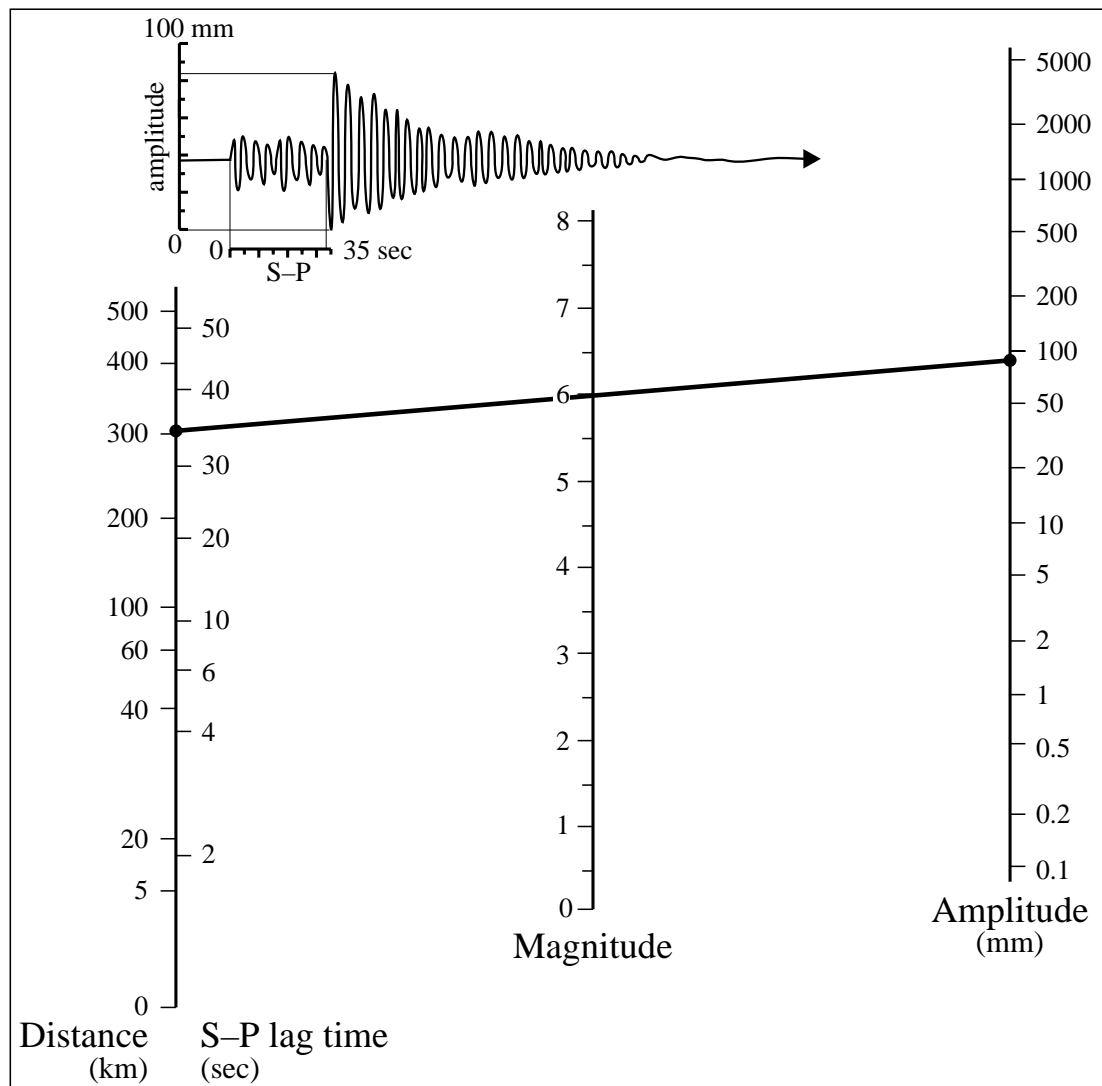
Figure 2.1. Method for determining the Richter magnitude of an earthquake from a seismogram. The maximum wave amplitude on the seismogram is connected with the epicentral distance. The intersection of that line with the magnitude axis gives the earthquake magnitude. (After Bolt, 1978)

Magnitude and Intensity

3) Using Figure 2.1, determine the Richter magnitudes for the earthquake data given in the table below.

Amplitude (mm)	Distance (km)	Richter Mag.
1	100	_____
10	100	_____
100	100	_____
10	5	_____
10	50	_____
10	500	_____

4) Looking at the first three earthquakes in the table above, what is the effect on Richter magnitude of a ten-fold increase in maximum seismic-wave amplitude? Why does this occur?

5) Looking at the last three earthquakes in the table above, what is the effect on Richter magnitude of a ten-fold increase in the distance between the recording station and the epicenter? Why does this occur?

It's important to note that Richter magnitude is not the only system for measuring earthquake energy. You may have noted that the list of earthquakes at the end of Exercise 1 included magnitudes with a variety of subscripts: M_s, M_b, M_w, and M_D. All of these magnitude scales are logarithmic scales, but different systems have advantages in different situations. For example, whereas Richter magnitude is based on the amplitude of the largest wave associated with a given earthquake, magnitude also can be determined using the largest body wave (M_b) or the largest surface wave (M_s). If surface waves cause a particular seismograph to go "off scale" (the amplitude is greater than the seismograph's range of motion), then the smaller body waves may still be used to calculate magnitude.

One particularly useful alternative to Richter magnitude is the *Moment magnitude scale* (M_w). Moment magnitude is based on the *seismic moment* of an earthquake, which is a direct measurement or estimate of the energy released by the earthquake. Seismic moment (M_o) can be calculated as follows:

$$M_o = \mu * D_{av} * A \tag{2.1}$$

where μ is the modulus of rigidity of the crust (about $3.3 * 10^{11}$ dynes/cm^2; Brune, 1968), D_{av} is the average displacement on the fault during the earthquake, and A is the total area of rupture on the fault. Seismologists often favor using seismic moment because it is the most physically-based estimate of earthquake energy. Seismic moment can be converted into a magnitude scale using the following equation (Hanks and Kanomori, 1979):

$$M_w = 2/3 * \log M_o - 10.7. \tag{2.2}$$

Example 2.2.

Find the seismic moment (M_o) of a M_w=7.5 earthquake.

The answer to this question is a straightforward solution of Equation 2.2:

$$7.5 = 2/3 * \log M_o - 10.7$$

simplifying:

$$3/2 * (7.5 + 10.7) = \log M_o$$
$$\log M_o = 27.3$$

The inverse of the logarithm function is the exponent function (10^x). The way to simplify a logarithm term is with the rule that $10^{(\log x)} = x$, so that:

$$10^{(\log M_o)} = 10^{(27.3)}$$
$$M_o = 10^{27.3}$$
$$M_o = 2.00 * 10^{27}$$

and the units of seismic moment are dyne·cm.

If the M_w=7.5 earthquake discussed above ruptures the surface with an average displacement (D_{av}) of 2.5 m, find the fault area (A) that ruptured during the earthquake.

This question uses the result from the last question ($M_o = 2.00 * 10^{27}$) and Equation 2.1:

$$M_o = \mu * D_{av} * A$$

$$2.00 * 10^{27} \text{ dyne·cm} = 3.3 \ 10^{11} \text{ dynes/cm}^2 * 2.5 \text{ m} * A$$

Converting the meters term into cm and simplifying:

$$2.00 * 10^{27} \text{ dyne·cm} = 3.3 * 10^{11} \text{ dynes/cm}^2 * 250 \text{ cm} * A$$

$$2.4 * 10^{13} \text{ cm}^2 = A$$

$$A = 2.4 * 10^9 \text{ m}^2$$

$$A = 2.4 * 10^3 \text{ km}^2 = 2400 \text{ km}^2$$

Magnitude and Intensity

MAGNITUDE OF THE 1994 NORTHRIDGE EARTHQUAKE

Exercise 1 introduced the Northridge earthquake just northwest of Los Angeles. This exercise will expand upon that example. It's important to note that, although it was the most damaging earthquake in U.S. history, the Northridge earthquake was definitely not the "Big One" that California fears. In fact it was over six times less powerful than the 1992 Landers earthquake that did relatively little damage. The major problem was that the Northridge earthquake struck in the middle of a densely-populated urban area.

6) Determine the Richter magnitude of the Northridge earthquake. Use the following steps:

        A) Measure the S-P lag time for each seismogram.

        B) Measure the maximum seismic-wave amplitude for each seismogram.

        C) Convert your amplitude measurements into mm using the scaling information provided with each seismogram.

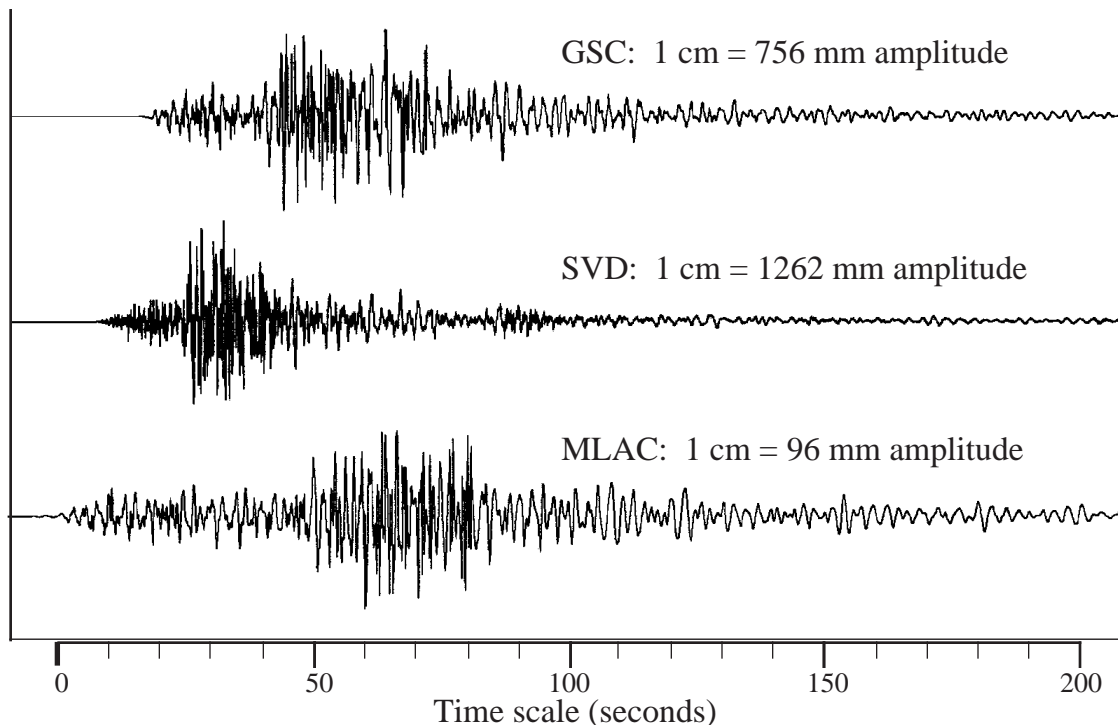   D) Plot lag time and amplitude on Figure 2.1 to determine magnitude.

Figure 2.2. Three seismograms that record the 1994 Northridge earthquake.

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7) Assume that the Moment magnitude (M_w) for the Northridge earthquake equals the Richter magnitude (M). What was the seismic moment (M_o) of that earthquake?

8) Aftershocks that followed the Northridge earthquake defined a fault plane about 15 km long, dipping about 40° to the south-southwest, with rupture from the focal depth (about 19 km) up to a depth of 8 km. Using this information (summarized in the diagram below), calculate the surface area (A) of the fault that caused the Northridge earthquake.
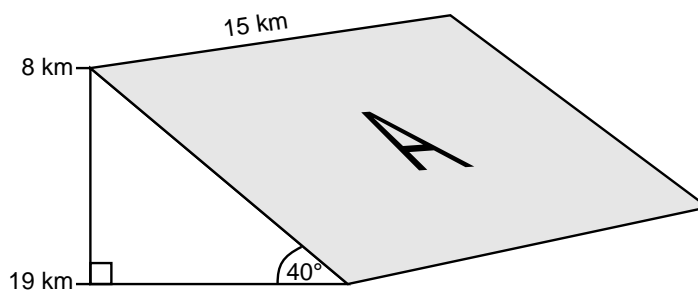
9) Using Equation 2.1 and your results from Questions 7 and 8, find the average fault displacement that occurred during the Northridge earthquake.

Magnitude and Intensity

10) 1.0 dyne·cm is the energy necessary to lift a 1.0 g mass a distance of 0.001 cm. Assume that the Northridge earthquake uplifted an area of 500 km² by an average of 35 cm, that uplift occurred from 8 km depth to the surface, and that the average density of the uplifted crust is 3000 kg/m³. What percentage of the earthquake's total energy (seismic moment) went into uplifting that area? Where does the rest of the energy go?

EARTHQUAKE INTENSITY

Earthquake intensity is defined as the strength of seismic shaking at a given location. Whereas an earthquake has just a single magnitude, it will have many different intensities at different locations. In general, areas closest to the epicenter experience the highest intensities, and shaking diminishes in strength farther away. This phenomenon is the result of seismic-wave *attenuation,* which is the reduction in wave amplitude and wave energy as they travel away from their source.

In order to study the patterns of earthquake intensity during different earthquakes, a system has been devised to assign specific numbers to different levels of shaking. The *Mercalli scale* was developed in 1902 and modified in the 1930s. The Mercalli scale assigns a numerical value, from Roman numeral I to XII, to the intensity of seismic shaking at any one particular location. The criteria for each Mercalli intensity are listed in Table 2.1. Figure 2.3 illustrates the distribution of intensities during an earthquake that struck southern Michigan in 1947. Note that the lines of equal intensity (called *isoseismal lines)* on Figure 2.3 are not perfect circles. The intensity of ground shaking can be influenced

strongly by local and regional geology, by focusing of seismic waves, and by near-surface sediments. For example, *material amplification* (amplification of shaking by near-surface material) can cause some of the worst damage during earthquakes. During both the 1906 and the 1989 earthquakes that struck San Francisco, the worst shaking damage occurred in the city's Marina District, which is built on artificial fill added to San Francisco Bay. Jets of fluidized sediment during the 1989 earthquake unearthed debris from buildings destroyed in 1906.

Figure 2.3. An earthquake that hit Michigan on Aug. 10, 1947 was felt across much of the Midwest. (After Stover and Coffman, 1993)

The descriptions of earthquake shaking used in the following exercise are summaries of the responses to 664 questionnaires mailed to post offices, police stations, and fire stations in the area affected by the 1994 Northridge earthquake (Dewey et al, 1995). You will use these summaries to assign a Mercalli intensity to each location (see Example 2.3).

Magnitude and Intensity

Table 2.1. Modified Mercalli scale (Abridged; After Wood and Neumann, 1931)

I.	Not felt, except by a very few, under especially favorable circumstances.
II.	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III.	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibrations like a passing truck.
IV.	During the day, felt indoors by many, outdoors by few. At night, some awakened. Dishes, windows, doors disturbed; cracking sounds from walls. Sensation like heavy truck striking building. Standing automobiles rock noticeably.
V.	Felt by nearly everyone; many awakened. Some dishes, windows, etc. broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI.	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Structural damage slight.
VII.	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly-built or badly-designed structures; some chimneys broken. Noticed by people driving.
VIII.	Damage slight in specially-engineered structures; considerable in ordinary structures. Many buildings with partial collapse. Panel walls thrown out of some frame structures. Fall of chimneys, factory stacks, columns, monuments, masonry walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water.
IX.	Damage considerable in all structures. Well-designed frame structures thrown out of plumb; partial collapse in many substantial buildings. Buildings shifted off foundations. Ground conspicuously cracked. Underground pipes broken.
X.	Some well-built wooden structures destroyed; most masonry and frame structures destroyed, including foundations. Ground badly cracked. Rails bent. Landslides considerable on river banks and other steep slopes. Shifted sand and mud.
XI.	Few, if any, masonry structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII.	Damage total. Waves seen on ground surface. Lines of sight distorted. Objects thrown upward into the air.

Example 2.3.

Assign a Mercalli intensity for the earthquake effects summarized below:

> On the UCLA campus, Royce Hall was closed because of damage to its two masonry towers. A 15 by 75 ft section of heavy ceiling fell in a campus auditorium. About one-third of the books in the University Research Library fell, piling up three feet deep in places. Elsewhere in the vicinity, masonry fences were destroyed; underground pipes were put out of service, plaster walls sustained large cracks; and some chimneys were damaged or fell.

As you compare this description with Table 2.1, you'll see that some of the details in the description are directly pertinent to the criteria in the table, and others are not. For example, damage to chimneys is a criterion for Mercalli intensities VI, VII, and VIII.   The description of the UCLA campus shows that some buildings were partially damaged and implies that most others sustained little or no structural damage. Mercalli intensity VII is closest, with its criterion, "Damage negligible in buildings of good design; slight to moderate in well-built ordinary structures."   Other details are consistent with shaking that was greater than intensity VI but less than intensity VIII.

INTENSITY OF THE 1994 NORTHRIDGE EARTHQUAKE

The Northridge earthquake was felt over an area in excess of 214,000 km² (82,000 mi²), from Ensenada, Mexico to Turlock in California's Central Valley to Richfield, Utah. As mentioned in Exercise 1, the earthquake killed 33 people and caused an estimated $20 billion in damage, making it at the time the costliest earthquake ever. In this exercise you will read a series of descriptions of seismic shaking and damage associated with the Northridge earthquake (from Dewey et al, 1995), assign Mercalli intensities to those descriptions, and map the isoseismal lines.

A) For each description listed on the following pages, assign a Mercalli intensity for that location.

B) When you have completed the list, plot the different intensities on Figure 2.4.

C) Assigning Mercalli intensities is not a purely objective process; you may wish to go back to some of those descriptions and reassess them after looking at the regional pattern.

D) The final step is to contour the intensities on Figure 2.4. Note that this is *not* a connect-the-dots puzzle. Isoseismal lines *enclose* all intensities equal to, or greater than, a given value.

E) Answer the questions that follow.

Acton_____: Many objects fell from store shelves; many homes sustained minor damage; pictures fell; a few windows cracked; small appliances moved.

Anaheim_____: A scoreboard structure at Anaheim stadium collapsed and damaged over 1000 seats. A few windows cracked; a few small objects overturned; a few people ran out of buildings. Felt by almost all people; many awakened. Hanging pictures swayed. Trees and bushes shook slightly to moderately.

Burbank_____: Police reported that the southwest section of town suffered the worst damage, including damage to the airport and the power plant. Masonry walls were destroyed and underground pipes broken. Many windows were broken out; light and heavy furniture was overturned. Many chimneys fell.

Chatsworth_____: Masonry fences were destroyed; underground pipes were put out of service; sidewalks and roadways sustained large cracks; many chimneys were broken at the roofline or fell. A beverage-can plant sustained extensive damage to manufacturing equipment and had to cease operations for an estimated ten weeks. One person was killed by falling objects in his house.

Compton_____: Plaster walls sustained hairline cracks and separated from ceiling or floor; a few chimneys were cracked; several small items were overturned; several items fell from store shelves; water splashed onto sides of swimming pools.

Downtown Los Angeles_____: The roof partially collapsed in the City Hall parking structure, and water lines broke in City Hall and in Parker Center. Interior and exterior walls sustained large cracks; some windows were broken out; a few small objects overturned and fell.

Fillmore_____: The picturesque old part of town, which contained many brick buildings built early this century, suffered extensive damage; some wood-frame houses were shifted off their foundations. Natural gas from a damaged pipeline ignited, and the fire spread to a nearby mobile home park.

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Glendale_____: In the Glendale Galleria shopping mall, storefront windows were broken, ceilings and walls were cracked, and shops sustained water damage. A six-story, unreinforced masonry building near the city hall sustained cracks in bearing walls. Questionnaire respondents reported that many glassware items and dishes broke, furniture and appliances were displaced, and shaking was felt in moving vehicles.

Hollywood_____: Unreinforced masonry buildings were substantially damaged, including cracks in walls and collapse of upper walls and corners. Some wood-frame apartments shifted on their foundations. A few tombstones shifted; some roads were cracked; and many chimneys were broken at the roof line.

Long Beach_____: A few small objects overturned; felt by almost all people; many people awakened. Hanging pictures swayed or fell. Trees and bushes shook slightly to moderately.

Malibu_____: At the J. Paul Getty Museum, equipment designed to protect against earthquake damage worked effectively, although several artifacts in transit from storage to display were damaged. Cracks reported in walls, chimneys, and windows; a few items shaken off store shelves.

Monrovia_____: Several chimneys were cracked or twisted; cracks in plaster walls, masonry fences, and windows; several small objects such as dishes fell and were broken; cars rocked moderately.

Northridge_____: Severe damage at the Northridge Fashion Mall, including partial collapse at Bullocks department store and partial to near-complete collapse of three parking structures. Many wood-frame apartment complexes were destroyed, including the Northridge Meadows complex in which 16 people died. The California State University at Northridge sustained $350 million in damage, including the collapse of a new concrete parking structure and structural damage to the steel-frame Oviatt Library. A Southern Pacific freight train derailed in Northridge, spilling 8000 gallons of sulfuric acid and 2000 gallons of diesel fuel.

Oxnard_____: Interior walls sustained a few large cracks; a few chimneys and windows cracked; several small objects overturned; light and heavy furniture and appliances were displaced; a few people ran out of buildings; moving vehicles rocked moderately.

Palmdale_____: Masonry fences, sidewalks, a few chimneys, a few windows, and stucco and plaster walls cracked. A few items were shaken off store shelves; a few people ran outdoors. The Vincent electric power substation was significantly damaged.

Piru_____: At the historic Piru mansion, chimneys fell, a porch pillar was jarred loose, and several statues fell and were broken. Elsewhere, masonry fences were partially damaged; streets and interior walls were cracked; light furniture and small appliances were overturned; and heavy furniture and appliances were displaced.

Redondo Beach_____: The Kings Harbor Marina sustained damage due to subsidence of fill. Plaster walls sustained hairline cracks; a few small objects overturned and fell; water splashed onto sides of pools.

Rosemead_____: A few tombstones fell; several small objects overturned and fell.

Santa Clarita_____: The Santa Clarita City Hall suffered an estimated $2 million in damage; the California Institute of the Arts sustained an estimated $50 million in damage; severe damage to some steel-frame buildings. Sand boils were observed at several locations.

San Fernando_____: According to preliminary estimates, 25% of concrete tilt-up buildings had serious structural damage, including partial collapse. Minor ground cracking occurred. A reinforced-masonry building under construction sustained significant damage.

Santa Monica_____: Masonry fences were destroyed; undergrounds pipes were put out of service; sidewalks and roads sustained large cracks; many chimneys had bricks fall or were broken at the roof line.

Santa Paula_____: Thirteen commercial buildings were damaged to the extent that they were "yellow-tagged" (access limited until repairs could be made). Shaking was felt by and/or awakened most to all people; people had difficulty walking or standing.

Sherman Oaks_____: 165 buildings were seriously damaged, including bad cracking of reinforced concrete columns in the Radisson Hotel, shear failures at the Four Seasons building, and severe damage and partial collapse of six concrete parking structures. There also was extensive damage to wood-frame structures, including collapse of 14 structures on stilts. Some ground cracking was reported.

Simi Valley_____: In some residential areas, reinforced chimneys and floor slabs were damaged, interiors and building contents were severely damaged, and some people were thrown from their beds. Sidewalks and roads sustained large displacements or buckled, and masonry fences and underground pipes were destroyed. Sand boils were reported, and ground spreading was widespread.

Tarzana_____: Businesses along Ventura Boulevard sustained an estimated $2.1 million in damage, mostly due to broken windows and damaged inventory. In the residential district, chimneys were damaged or destroyed in some areas, although houses in other areas sustained no damage visible from the outside. Masonry fences were destroyed; underground pipes were put out of service; sidewalks and roads cracked or buckled.

Thousand Oaks_____: Several homes sustained damage, most of which consisted of cracks in interior walls, although there were isolated locations of stronger damage. Masonry fences and walls partially fell; some windows were broken out; many small objects overturned and fell; light furniture and small appliances were displaced; standing vehicles rocked moderately; moving vehicles slightly.

Topanga_____: Masonry fences partially fell; underground pipes cracked; cracks in walls, chimneys, and windows. Several dishes and knickknacks were broken. Light furniture and small appliances were displaced. A few people ran out of buildings.

Tujunga_____: Masonry fences partially fell; underground pipes were cracked; walls sustained hairline cracks; several small objects overturned; several dishes and knickknacks were broken; light furniture was displaced; felt strongly in standing and moving vehicles.

Whittier_____: Many objects fell from shelves; many homes sustained minor damage.

Other sites_____: A number of sites in the area covered by Figure 2.4 reported Mercalli intensity V shaking. Some of these sites are indicated on the figure.
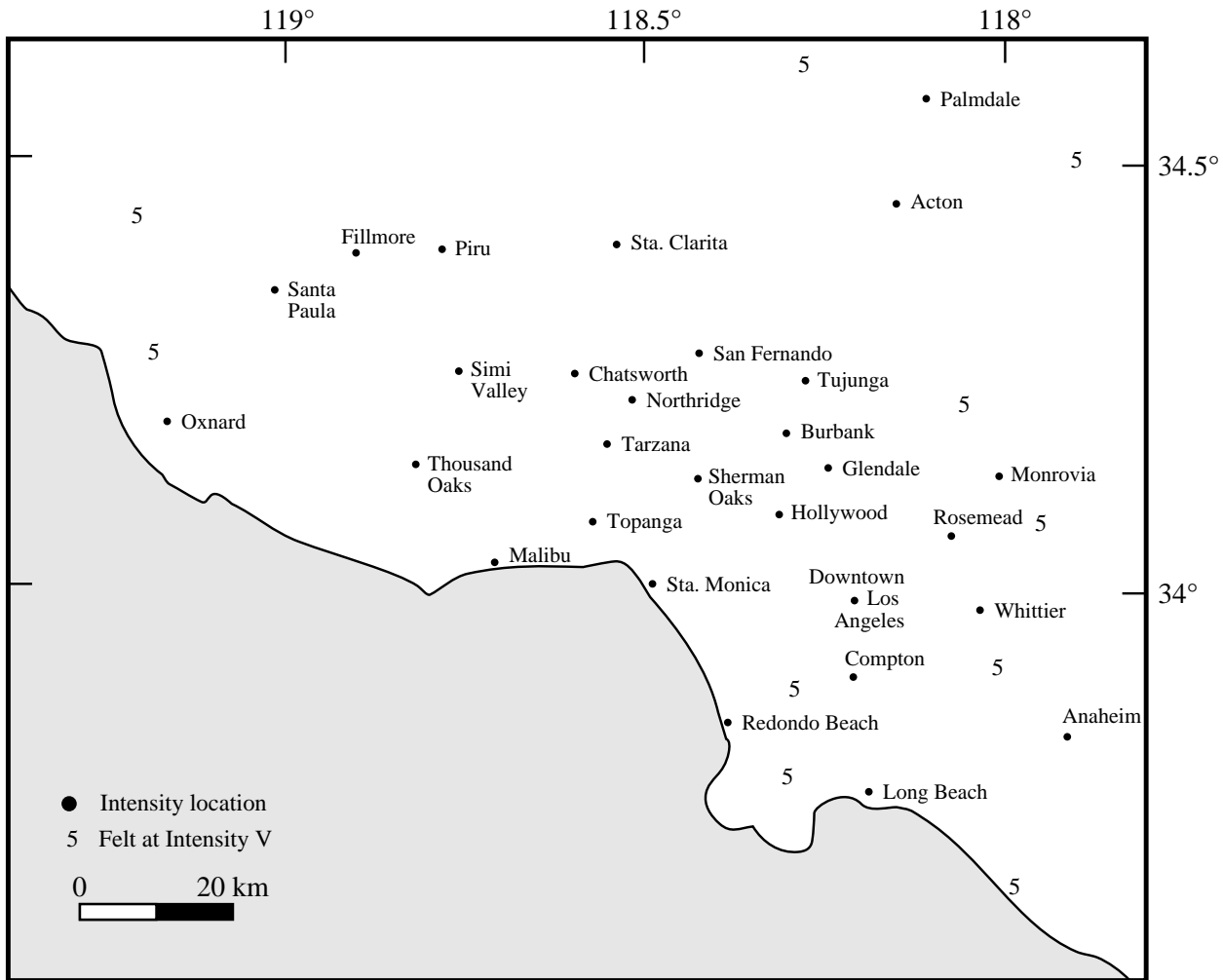
Figure 2.4. Location map for the greater Los Angeles metropolitan area.

11) Are the isoseismic lines on the map perfect circles? If not, why not?

12) The maximum intensity reported for the Northridge earthquake by the U.S. Geological survey was IX.   Intensity summaries like the ones in this exercise (as well as television and newspaper reports) focus on destruction and deemphasize buildings or areas that were not damaged. In what way would this lead you to overestimate Mercalli intensities?

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