The first three things people want to know about an earthquake is When, Where, and How Big. There are two different approaches to talking about earthquake size: how strongly the ground shook and how much energy was released at the earthquake source. These two different measures of earthquake size have resulted in sub-disciplines of seismology – Intensity/Strong Motion and Magnitude.

Ground shaking strength and extent was the first measure of earthquake size. Robert Mallet, an Irish geologist in the 19th century, was the first to coin the term *intensity*. He undertook a systematic study of the Great Neapolitan Earthquake in 1857. He mapped the degree of damage to structures and interviewed residents as to their experience of the earthquake and found that the most heavily damaged buildings were concentrated in a small central zone. The relative damage and strength of shaking decreased in roughly concentric zones moving away from the center.

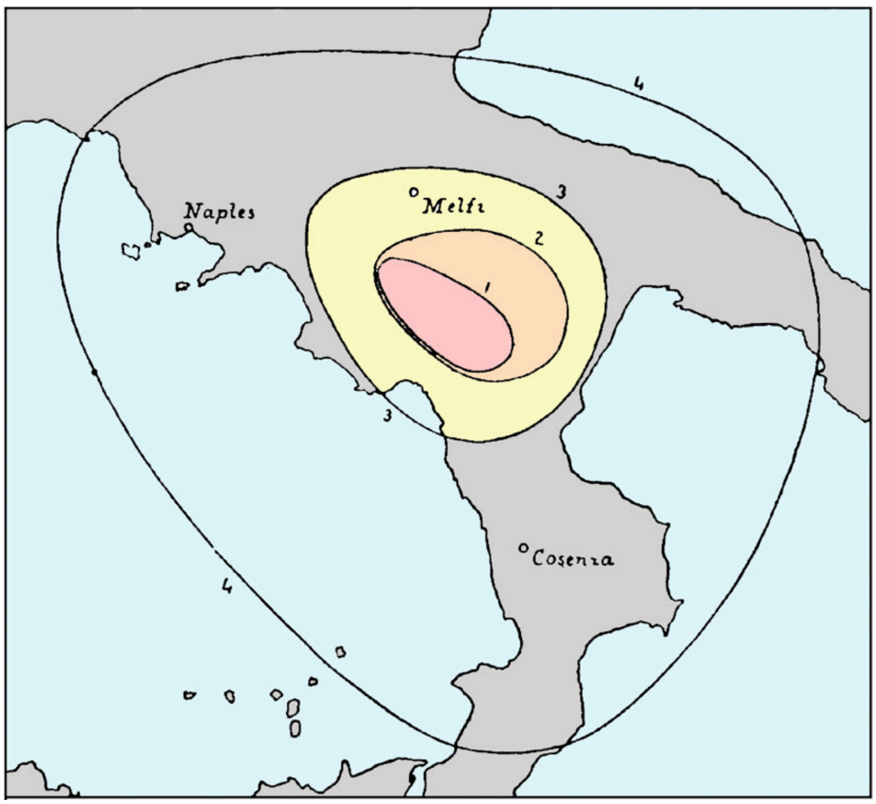


Figure 1. Robert Mallet's intensity map of the 1857 Italy earthquake. Mallet introduced the idea of isoseismal lines, contours of equal shaking strength. Buildings in the pink zone (labeled 1) were demolished by the ground shaking. In the orange zone (2), buildings were damaged but few had collapsed. In the yellow zone (3), the damage to buildings was minor.

Mallet was the first to introduce the concept of *isoseismal lines*, contours of equal shaking strength. His first isoseismal zone (pink area in figure 1) contained towns where nearly every building had collapsed and loss of life was very high. His second zone bounds the area where loss of life was still high but fewer buildings had collapsed. In the third zone, most buildings suffered only minor damage and although many people were injured, few people were killed. Mallet used his isoseimals to estimate the location of the earthquake epicenter (in the center of zone 1). He considered the third isoseismal to be the limit of the disturbed zone, where buildings had suffered damage. In zone 4, (gray in figure 1), the earthquake was felt, but no damage to structures was observed.

Seismologists continued to use isoseismals to estimate epicenter collation until the late 1800s and the deployment of seismographs. Geologists studying earthquakes built on Mallet's isoseismal idea and developed a number of different intensity scales over the next century. Mallet defined four intensity zones, numbering them from 1 to 4 from strongest to weakest shaking. Italian geologist Michele Stefano Conte de Rossi and Swiss scientist François-Alphonse Forel of Switzerland developed the first widely adopted intensity scale in the 1870s. The Rossi-Forel scale recognized that observations of shaking strength outside of the disturbed zone of building damage could be used to refine the isoseismal map and introduce more shaking levels. The earthquake report on the 1906 San Francisco earthquake feature Rossi-Forel intensity maps (figure 2).

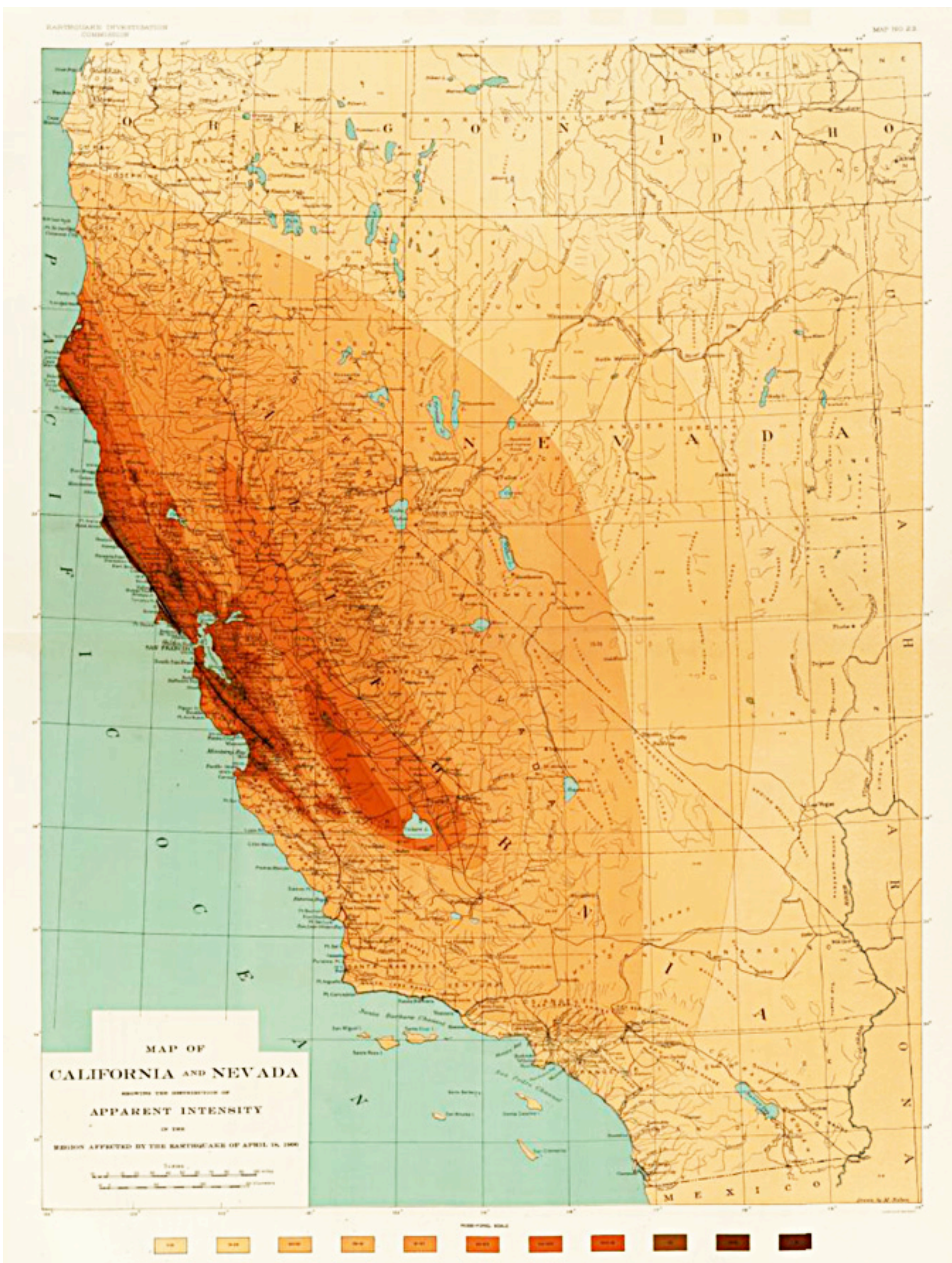


Figure 2. Rossi-Forel intensity map of the 1906 San Francisco earthquake. The map defines ten levels of shaking denoted by the colors at the bottom of the map.

The 1873 version of the Rossi–Forel scale used in figure 2 had 10 intensity levels:

I. Microseismic tremor. Recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds. The shock felt by an experienced observer.
II. Extremely feeble tremor. Recorded by several seismographs of different kinds. Felt by a small number of persons at rest.
III. Feeble tremor. Felt by several persons at rest. Strong enough for the direction or duration to be appreciable.
IV. Slight tremor. Felt by persons in motion. Disturbance of movable objects, doors, windows, cracking of ceilings.
V. Moderate tremor. Felt generally by everyone. Disturbance of furniture, ringing of some bells.
VI. Strong tremor. General awakening of those asleep. General ringing of bells. Oscillation of chandeliers, stopping of clocks, visible agitation of trees and shrubs. Some startled persons leaving their dwellings.
VII. Very strong tremor. Overthrow of movable objects, fall of plaster, ringing of church bells. General panic. Moderate to heavy damage buildings.
VIII. Damaging tremor. Fall of chimneys. Cracks in the walls of buildings.
IX. Devastating tremor. Partial or total destruction of buildings.
X. Extremely high intensity tremor. Great disaster, ruins, disturbance of the strata, fissures in the ground, rock falls from mountains.

The Rossi-Forel scale is still used in some countries today, including the Philippines. It is the foundation of other more widely-used intensity scales, including the Modified Mercalli scale still used in the Untied States.

The Mercalli scale began with a revision of the Rossi-Forel scale by Italian vulcanologist, Giuseppe Mercalli in 1884. In 1902 the ten-degree Mercalli scale was expanded to twelve degrees by Italian physicist Adolfo Cancani. It was later completely re-written by the German geophysicist August Heinrich Sieberg and became known as the Mercalli-Cancani-Sieberg (MCS) scale. The Mercalli-Cancani-Sieberg scale was later modified and published in English by Harry O. Wood and Frank Neumann in 1931 as the Mercalli-Wood-Neumann (MWN) scale. Lori Dengler and Robert McPherson made additional modifications in 1993 to apply the scale to rural areas. The scale is known today as the Modified Mercalli scale (MM) or Modified Mercalli Intensity scale (MMI) and is the basis of modern intensity scales.

Simplified Modified Mercalli Scale

(after Wood and Neumann, 1931; Toppozada and others, 1981; Dengler and McPherson,1993)

I Not felt. <u>Rare</u> reports of slight swaying of trees or chandeliers, ripples appearing on bodies of water, and doors slowly swinging.

II Felt by a few persons especially those on upper floors, seated or lying down, or by sensitive or nervous persons. Hanging objects may swing, especially if delicately suspended, some may notice ripples on lakes or swimming pools. Little or no noise reported. Sleepers not awakened.

III Felt by many people inside, although not always immediately recognized as an earthquake; many notice a light vibration, swaying objects, swinging of doors, creaking of walls, light rattling of objects. Parked cars may rock slightly. Most are not frightened. A few light sleepers may be awakened, especially those on upper floors.

IV Felt by all inside and some outside; many awakened; frightens some, particularly those apprehensive from previous experiences. Vibration like that due to the passing of heavy trucks; distinctive rattling of dishes, glassware, windows, doors and creaking of walls. Hanging objects often swing; pictures on walls may be knocked askew. Liquids in open vessels such as aquariums and toilet bowls may slosh but rarely spill. Standing cars rocked noticeably. Virtually nothing falls or is knocked from shelves.

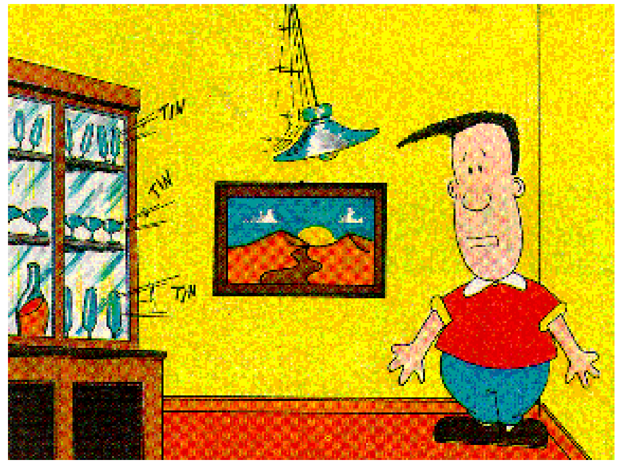


Figure 2. At the intensity IV level, everyone notices the shaking. Dishes rattle, lamps swing, water may slosh.

V Felt by most outside; many frightened (particularly those not accustomed to earthquakes), some run outdoors. Frequent reports of buildings trembling/groaning and swinging objects, moving doors and shutters. A few items may topple or fall, but most do not; occasional broken glassware and crockery. Hanging pictures knock against walls or swing out of place; liquid may spill from well-filled open containers; pendulum clocks stopped or started; trees and bushes shaken slightly. Almost all sleepers awakened.

VI Felt by all; many are frightened, many perceive difficulty in walking; almost everyone reports a few objects off shelves; some furniture may be displaced; some minor structural damage such as cracks in chimneys and plaster, cracking of large store windows not designed to withstand earthquake shaking. (in heavily populated areas, some injuries may be reported, but typically of a minor nature). Some reports of dead limbs and tree tops falling down; occasional rock fall from steep or unstable slopes. May be noticed by persons driving at slow to moderate speeds - but not always recognized by drivers as an earthquake.

VII Felt by all; frightens most; most find it difficult to stand or walk; non structural damage is widespread - all report many items off shelves; latched cupboards and refrigerator doors may be thrown open; very heavy items such as wood stoves and concrete tank lids likely to be displaced or tipped over;.noticed by all persons driving cars. Significant damage to unreinforced masonry structures; many chimneys down and damaged; trailers and houses not securely tied to foundations suffer foundation damage. (injuries are likely, but not widespread)

Figure 3. Adobe buildings in Peru were severely damaged in intensity VII shaking in 2001.

VIII Felt by all, frightens all, many report falling or being knocked to ground. Major damage to unreinforced masonry buildings. Difficult to impossible to drive a car; insides of houses 'trashed' - literally everything not securely tied down is displaced. Cracked and disturbed ground common; all very heavy objects (like wood stoves) are displaced. (Injuries widespread and some fatalities likely if earthquake centered in populated areas)

Figure 4. Santa Rosa City Hall, 1906

IX Threshold of structural damage in buildings designed to resist earthquake motion (like SF Bay Bridge). Significant structural damage to some well built wood frame buildings securely tied to foundations and modern engineered larger structures designed to resist strong ground motion. Many underground pipes break, major damage to reservoirs. (Significant loss of life in heavily populated areas)

Figure 5. Cypress Structure, Oakland. Damage from the 1989 Loma Prieta Earthquake.

X Some well-built wooden structures destroyed, damage to steel-frame modern buildings, most masonry and frame structures destroyed with foundations. Rails bent. (Great loss of life in heavily populated areas)

Figure 6. 21-story steel-frame building, Mexico City, 1985.

Intensities higher than X are almost never assigned , but for the sake of completeness, they are included below.

XI Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.

XII Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Isoseismal maps

Isoseismal maps provide the most detailed information about earthquakes that occurred before seismic instruments, and they still provide a good visual representation of earthquake impacts of modern events. If the earthquake source were simple, like an explosion, and produced uniform energy in all directions originating from a single point, and the geology was the same everywhere, we'd expect the isoseismal map to look a little like a bull's eye target (figure 7).

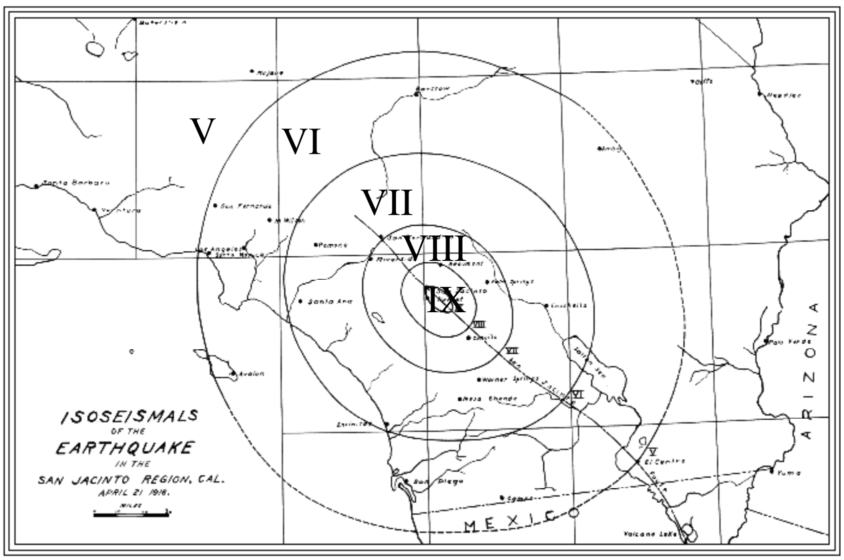


Figure 7. Isoseismal map of the 1918 earthquake near San Jacinto.

One of the reasons the isoseismals are such simple shapes in figure 7 is because there is relatively little data. In 1918, very few people lived in Southern California and so the lines aren't constrained by very many reports. Most recent earthquakes with many reporting sites tend to show much more complexity. Figure 8 shows the isoseismal maps of the 1958 Montana earthquake and the 1989 Loma Prieta earthquake.

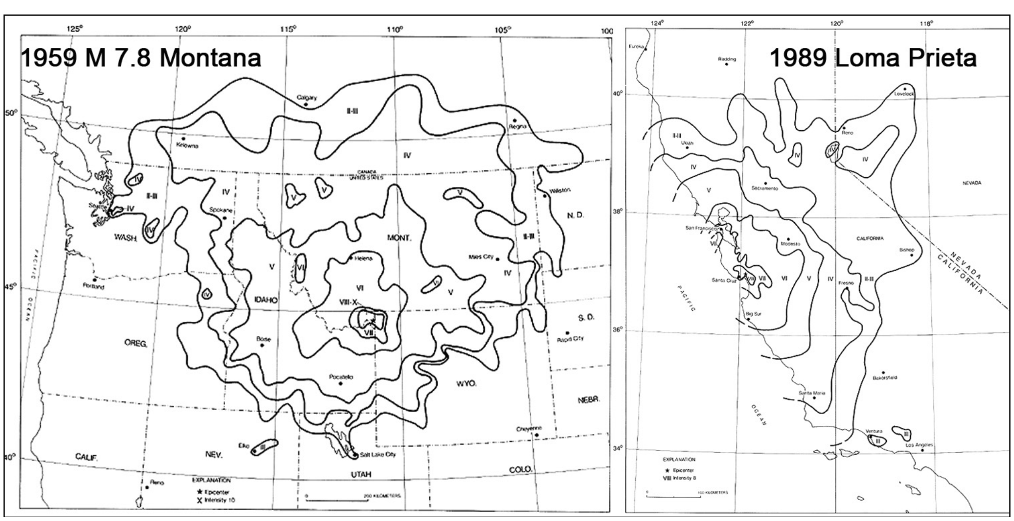


Figure 8. The isoseismal lines of the 1959 Montana and 1989 Loma Prieta earthquakes are much more irregular than the 1918 San Jacinto earthquake.

Complexities in the ground shaking pattern are caused by a number of factors including local and regional geology, soil types and water saturation levels, topography and earthquake source characteristics. Some of the strongest effects are caused by soil amplification, liquefaction and hill top amplification.

Soil amplification:
Unconsolidated soils and artificial fill shake more strongly than bedrock. You are examining this relationship in Home Problem #4 by comparing the ground shaking strength to the geology of the San Francisco Bay Area. We see the same relationship in the 1989 Loma Prieta earthquake. Figure 9 shows a simplified map of San Francisco and the measured shaking strength. The areas of strongest shaking coincide with artificial fill and the weakest shaking zones correspond to more competent bedrock.

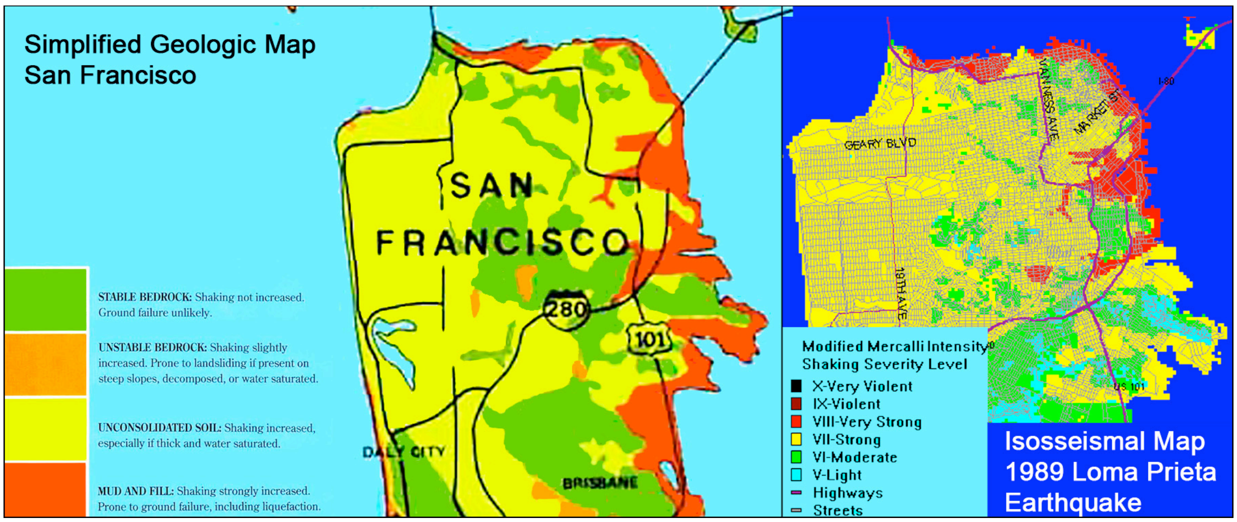


Figure 9. Comparison of San Francisco geology and the 1989 M 6.9 Loma Prieta earthquake isoseismal map.

Seismic hazard maps often take into account the local and regional geologic and soil conditions. Figure 10 shows the estimated soil amplification effects for the greater San Francisco Bay Area. Note that the highest shaking zones are the areas of artificial and natural fill near the Bay. *Alluvial* fill in valleys show high shaking levels when compared to the bedrock areas on hills.

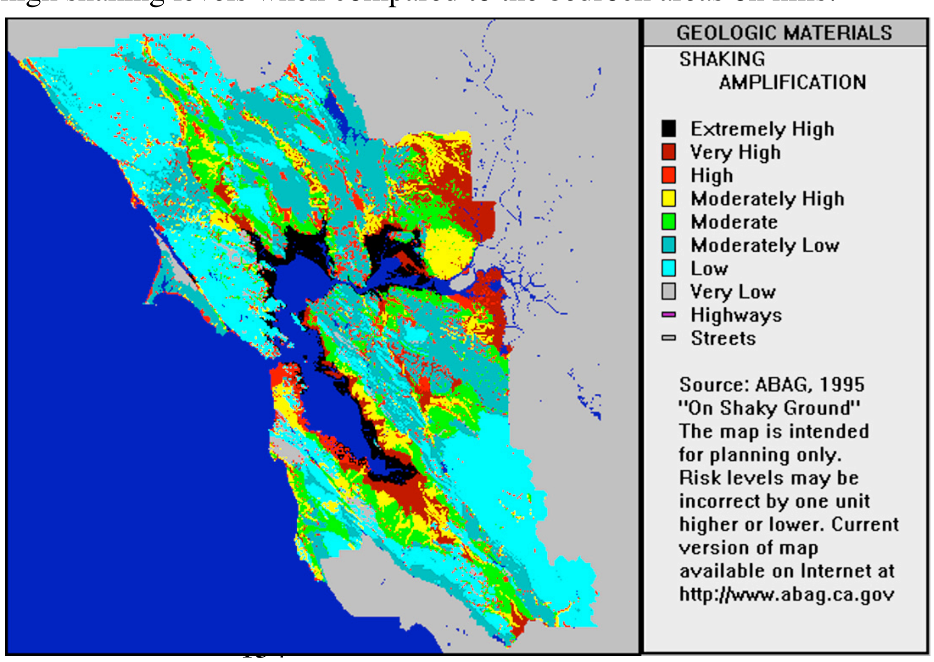


Figure 10. Shaking hazard map of the Greater San Francisco Bay Area is related to soil and bed rock type. The black and dark red areas correspond to areas of artificial fill. Yellow and light red areas show the unconsolidated sediments in valley bottoms. Blue areas are bed rock. The actual pattern of ground shaking in any particular earthquake will differ from this map and depend on epicenter location, magnitude and faulting characteristics.

Liquefaction:
Areas of artificial fill and soft sediments not only shake more strongly, they may liquefy as well. Liquefaction is the result of saturated ground behaving like a liquid when the ground shakes. You were introduced to the phenomenon in NOTES: Paleoseismology as the process leaves features that geologists can recognize centuries later. Figure 11 illustrates the liquefaction process. A layer of unconsolidated sand or silt is normally quite "solid" to stand or build on. The sand grains are loosely packed but rest on top of each other to create an apparently firm base. But the grains are loosely packed and the void spaces between the grains are large. If the sand layer is saturated, the stage is set for liquefaction. Earthquake vibrations act as a giant compaction machine. The shaking causes the sand grains to settle, forcing the water that was in the pore space upwards. While the water is moving, the sand grains are no longer resting solidly on each other and the whole layer suddenly acts as a liquid. Cars and buildings may sink into the ground and roads break up and settle. As soon as the shaking stops, the sand grains settle once again into contact and the materials appears firm again.

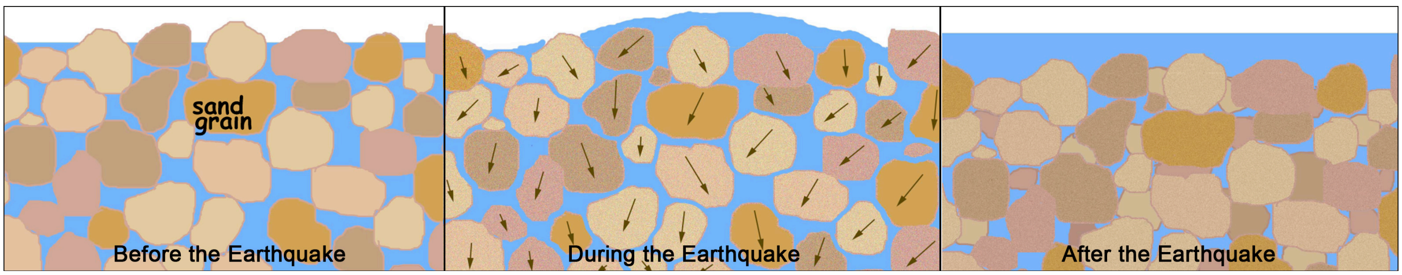


Figure 11. Liquefaction. Before the earthquake (left), sand grains are loosely arranged with grains touching and creating a solid framework. During the earthquake (center), shaking causes the grains to settle, forcing the water upwards and breaking the grain – to – grain contact. After the shaking stops (right), the grains resettle and regain contact with each other.

Liquefaction may leave a spectacular array of effects at the earth's surface (figure 12). The water being forced upwards is often concentrated in narrow zones, creating small water volcanoes called *sand blows*. If liquefaction occurs beneath a slope, the ground may spread apart creating fissures and breaking up any structures on top of the liquefiable zone.

Figure 12. Liquefaction in action. Left: Juan Mendez demonstrates how high the water squirted out of the ground in his field near Camana, Peru in the 2001 M 8.4 earthquake. Note the sand blow (arrow) that was left afterwards. Center: Apartment buildings toppled during liquefaction in the 1964 M 7.5 Niigata, Japan earthquake. The buildings had shallow foundations and slowly tilted over when the ground liquefied in the shaking. Right: Lateral spreading caused by liquefaction of the banks of the Eel River near Port Kenyon, Humboldt County during the 1906 M 7.8 San Francisco earthquake.

Hilltop amplification:
In most cases, bedrock areas of higher ground don't shake as strongly as the valley bottoms where thick sediments produce soil amplification effects. One exception is on the top of a hill.

If the ground were flat, the seismic waves will input the same level of shaking everywhere. But a hill will concentrate the shaking (figure 13). Hilltop amplification is a particular problem in Italy where many ancient towns were constructed on hilltops for fortification purposes. These hilltop towns are an important part of Italy's historical legacy and an important tourist draw. Unfortunately, the combination of hilltop amplification and older, unreinforced structures can be deadly as in the 1980 M 6.0 Irpinia earthquake.

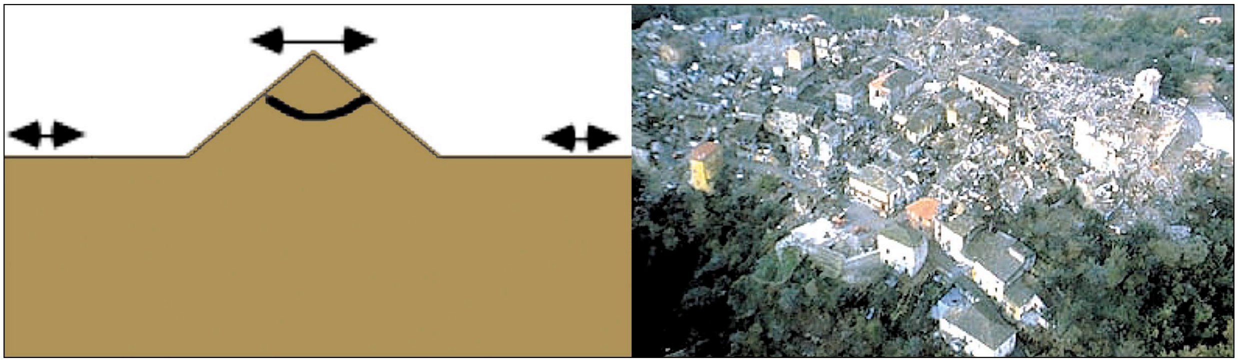


Figure 13. Hilltop amplification is the result of the seismic wave energy being concentrated at the top of a hill. Left: If the ground were flat, the ground shaking is some uniform value as represented by the arrows to the left and right of the hill. The hilltop concentrates the seismic energy, resulting in much strong shaking (represented by the longer arrow at the top of the hill). Irpinia, Italy felt the effects of hilltop amplification in the 1980 M 6.9 earthquake. Notice how the damage is concentrated near the peak of the hill.

Other intensity scales

In the United States, the levels in the Modified Mercalli Scale still provides the basis for intensity values and measurements, although the methodology for collecting intensity data has changed. In 1998, Dengler and Dewey introduced the Community Internet Intensity scale based on questionnaires first developed at HSU) that quantified responses so that a statistically valid methodology could be used for averaging and calculating a numerical response for communities. This methodology lent itself to collecting data on-line and in 1999, the USGS led by David Wald incorporated the Dengler-Dewey technique into the Did You Feel It web site:
http://earthquake.usgs.gov/earthquakes/dyfi/
This has now become the primary way of collecting intensity data in the United States.

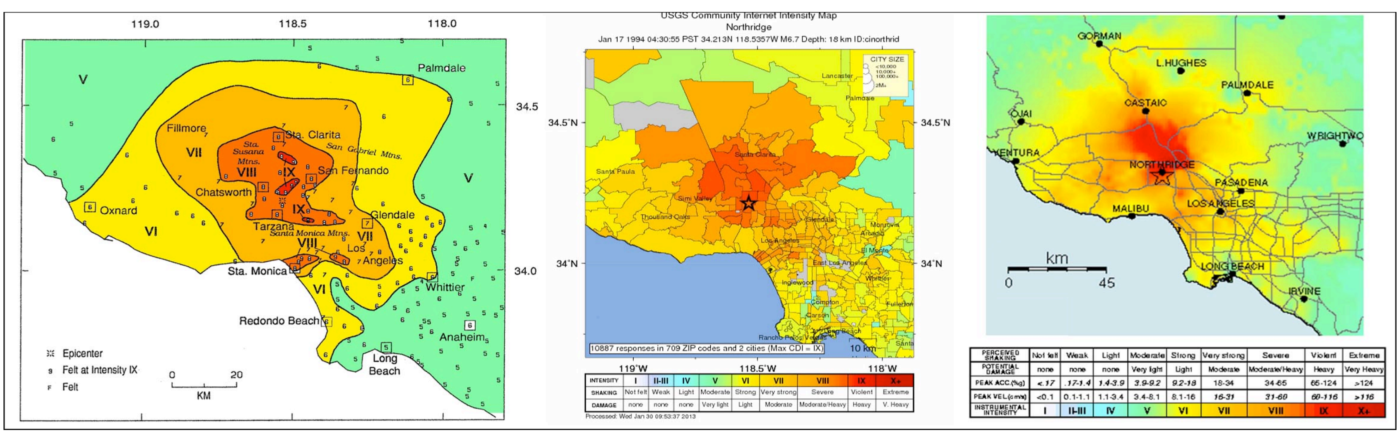


Figure 14. Different ways of displaying ground shaking information, 1994 Northridge earthquake. Left: conventional isoseismal map based on field reconnaissance and survey data. Center: Did You Feel It map based on public on-line responses to a survey questionnaire. Data is grouped according to zip code. Right: Shakemap based on strong motion seismic data. Note that all three maps show similar peak ground shaking and shaking patterns.

Another way of displaying shaking strength is to use the information from *strong motion instruments*, seismographs designed to measure accelerations. There will be more about strong motion and accelerations in the NOTES on Earthquake Engineering. The USGS has developed a technique to convert strong motion data into an equivalent intensity map. These maps are called *Shakemap*, and they have the advantage that they can be displayed within minutes of an earthquake and can be used by responders to identify the areas of greatest need. The disadvantage of Shakemap is that they require instruments and most parts of the world any many parts of the United States don't have the sufficient instrument coverage to make accurate Shakemaps based on instrument data alone. Figure 14 compares a conventional isoseismal map to the Did You Feel It map and Shakemap for the 1994 *M 6.7* Northridge earthquake.

Outside of the United States, other intensity scales are used. The Japanese Meteorological Agency (JMA) uses a decimal scale that ranges from 0 – 7. Europeans use a 12 point scale that is somewhat similar to the Modified Mercalli Scale called the European Macroseismic Scale (EMS). In looking at intensity maps, it is important to determine what scale is being used.

References:

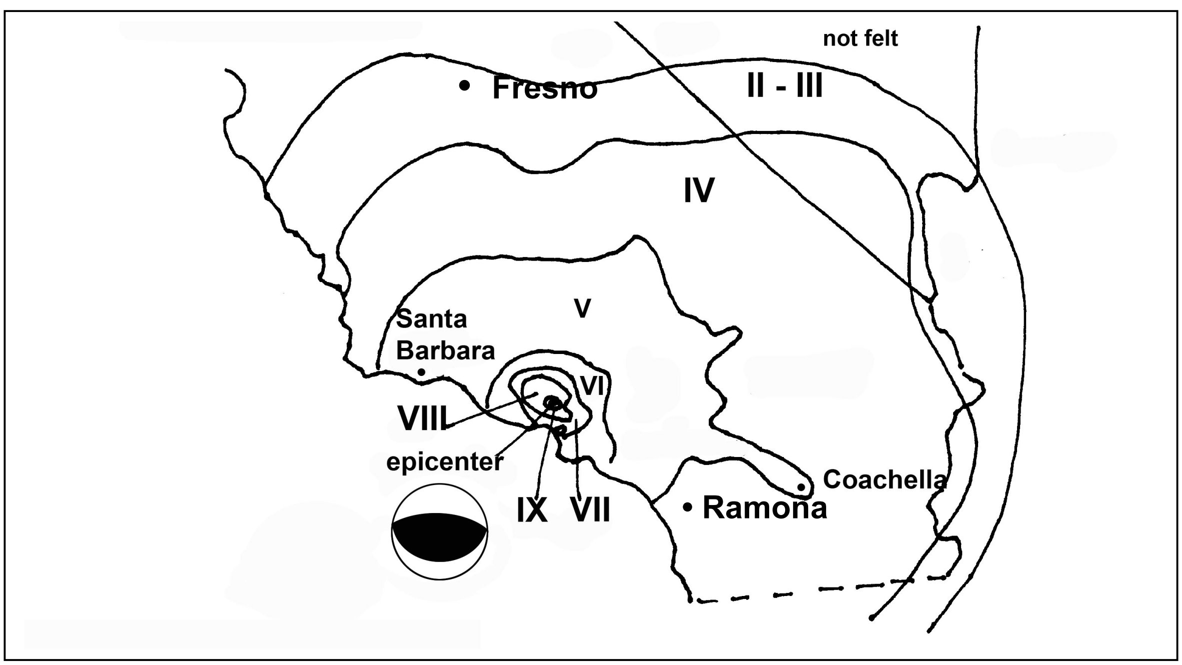
L.A. Dengler and J. Dewey, (1998). An intensity survey of households affected by the Northridge California, Earthquake of January 17, 1994, Bulletin of the Seismological Society of America, vol. 88 No. 2, p 441-462.

Wald, D., Quitoriano, V., Dengler, L.A., Dewey, J. W., (1999). Utilization of the Internet for Rapid Community Intensity Maps, Seismological Research Letters, Vol. 70, No. 6, 680-697.

Review Terms: *Did You Feel It, hilltop amplification, intensity, isoseismal line, isoseismal map, lateral spreading, liquefaction, Modified Mercalli scale, Rossi-Forel Scale, Shakemap, soil amplification*

Review Questions:

The sketch below is an isoseismal map of the 1994 Northridge earthquake. Use it to answer the questions on the next page. The map also shows the epicenter of the Northridge earthquake and the "beach ball" focal mechanism determined by seismologists shortly after the earthquake and you should know what it means.



1. Isoseismal maps show the distribution of:

a) fault slip
b) historic epicenters
c) shaking strength and damage
d) magnitude
e) earthquake risk

2. From the map, Fresno most likely experienced an intensity of:

a) II
b) IV
c) VI
d) VII
e) VIII

3. Santa Barbara experienced an intensity of V (5) in this earthquake. Which of the following best describes the type of effects in Santa Barbara for this earthquake?

a) All structures, even well-engineered ones, were severely damaged.
b) Damage to chimneys, broken windows, many items knocked off shelves.
c) A few items toppled over or were knocked from shelves, no other damage.
d) Most people felt it but nothing was knocked over or damaged.
e) Very few people felt the earthquake.

4. Coachella, located 140 miles from the earthquake, experienced an intensity of V(5) while Ramona located 130 miles from the epicenter experienced a IV (4). A likely reason is:

a) Construction methods in Coachella probably aren't as good as in Ramona
b) Coachella is located on softer ground than Ramona.
c) There are more faults close to Coachella than Ramona.
d) The people in Coachella are more used to earthquakes and don't react as strongly.
e) There weren't as many seismic instruments in Ramona as in Coachella.